LHCb and Belle II: present status and expectations

ECFA - Flavour anomalies:

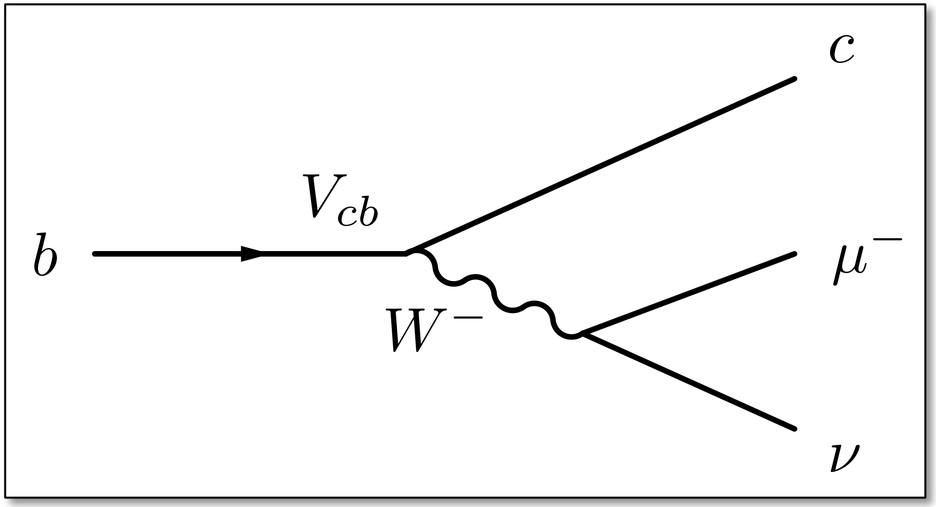
What can present and future experiments contribute to the understanding of this problem

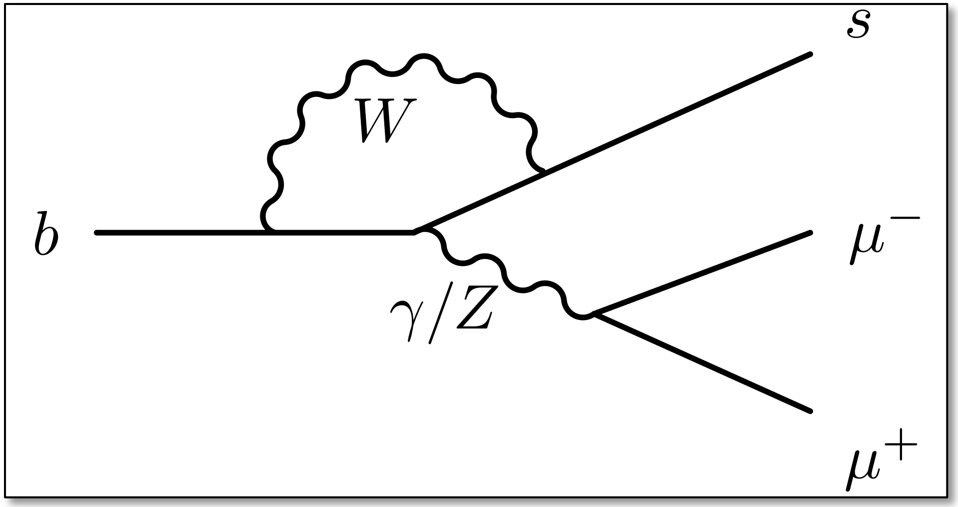
22 Jul 2022

Niels Tuning (LHCb, Nikhef)

(with thanks to Diego Tonelli, Jim Libby and Elisa Manoni from Belle II)

CC and FCNC





Semileptonic
CC
$b \rightarrow c l^- \nu$

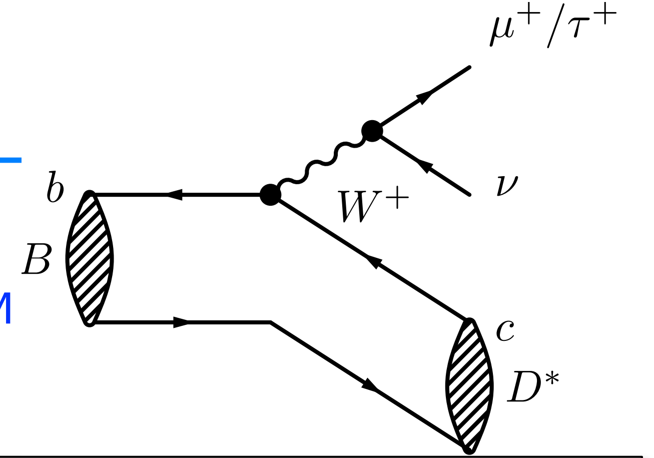
"Semileptonic"
FCNC EWP Penguin
$b \rightarrow s l^+ l^-$

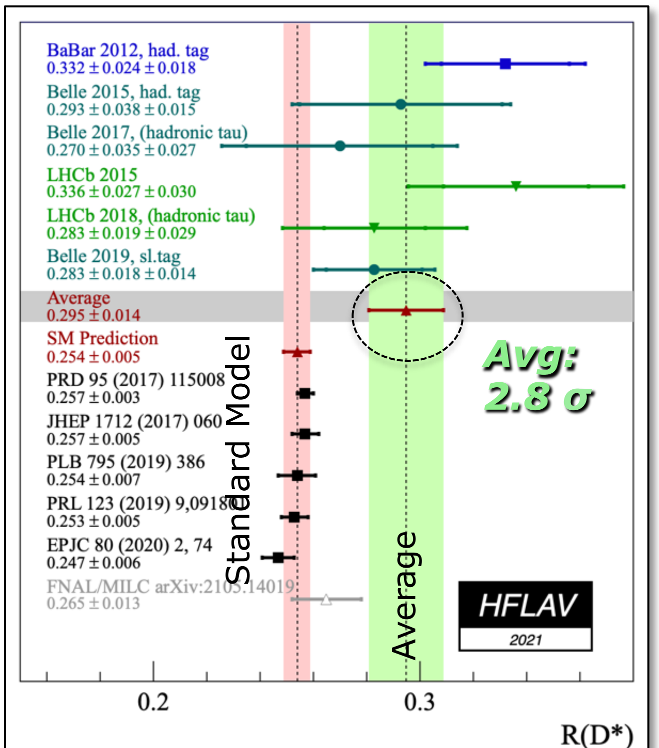
Outline

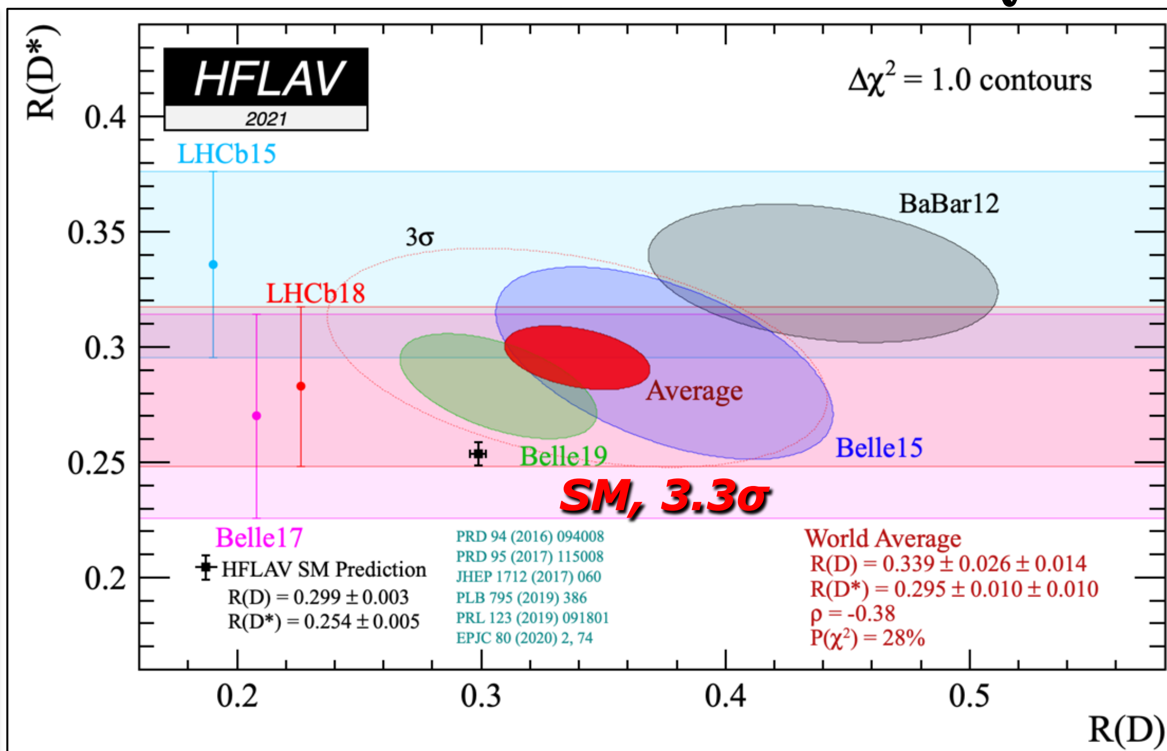
- CC: $b \to c l^- \nu$
  - $R(D^{(*)})$
- FCNC: $b \to s l^+ l^-$
  - $B_s^0 \to \mu^+ \mu^-$
  - Decay rates
  - Angular analyses
  - Lepton flavour ratios
- Effective couplings
- Prospects
  - Belle II
  - LHCb Upgrade 1
  - LHCb Upgrade 2

b→cl⁻ν : R(D$^{(*)}$)

- LFNU in CC tree decays?
  - τ-excess in b→c transitions, sensitive to TeV BSM







$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)}$$

$$\mathcal{R}(J/\psi) = 0.71 \pm 0.17\,(\text{stat}) \pm 0.18\,(\text{syst})$$

LHCb Coll. arXiv:1711.05623

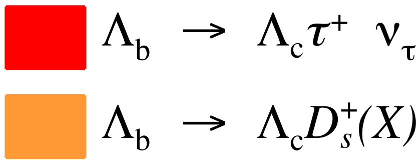
Recent measurement of $B(\Lambda_b \to \Lambda_c \tau \nu)$ (LHCb)

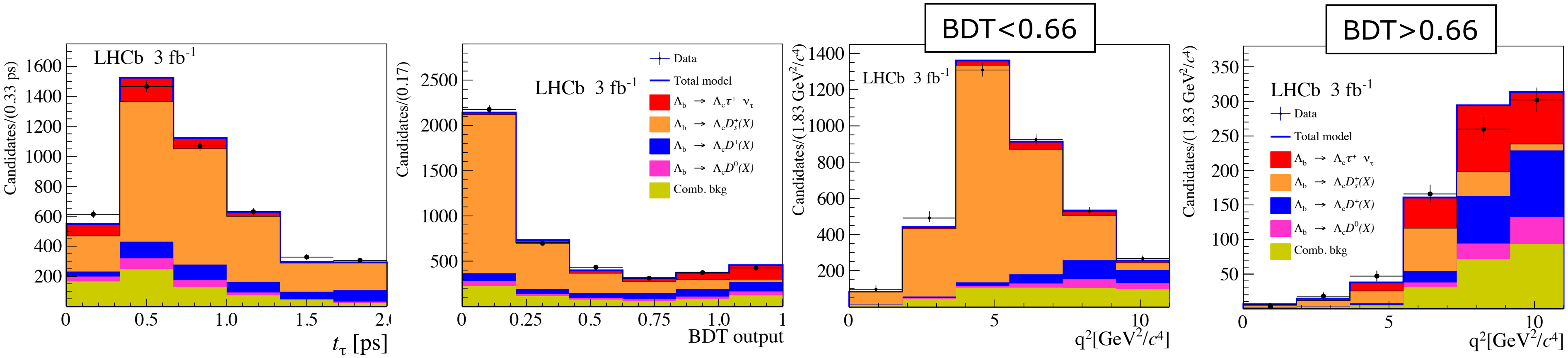
- New result on semileptonic anomalies
  - Hadronic tau decays

- Measure

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi)} = \frac{N_{\text{sig}}}{N_{\text{norm}}} \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}} \frac{1}{\mathcal{B}(\tau^- \to 3\pi(\pi^0)\overline{\nu}_\tau)}$$

- Simultaneous 3D fit to: τ, BDT, q^2
  - Discriminate $\Lambda_b \to \Lambda_c \tau \nu$ from $\Lambda_b \to \Lambda_c D_s X$





LHCb Coll. arXiv:2201.03497

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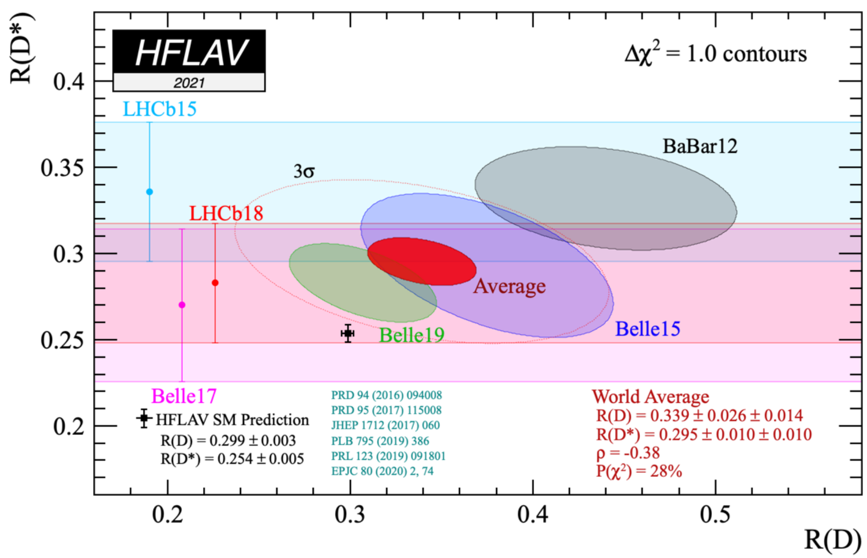
- First observation of $\Lambda_b \to \Lambda_c^+ \tau^- \nu$ at 6.1σ
  - Using BR($\Lambda_b \to \Lambda_c \pi\pi\pi$):
  - Using BR($\Lambda_b \to \Lambda_c \tau\mu$):

LHCb Coll. arXiv:2201.03497

$$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau) = (1.50 \pm 0.16 \pm 0.25 \pm 0.23)\%$$
$$\mathcal{R}(\Lambda_c^+) = 0.242 \pm 0.026 \pm 0.040 \pm 0.059$$



$\mathcal{R}(\Lambda_c^+)$

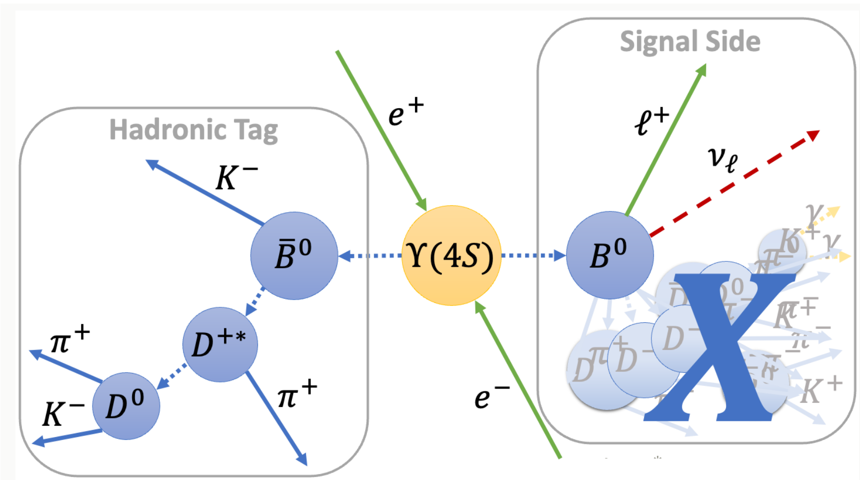
SM: $R(\Lambda_c) = 0.333 \pm 0.010$

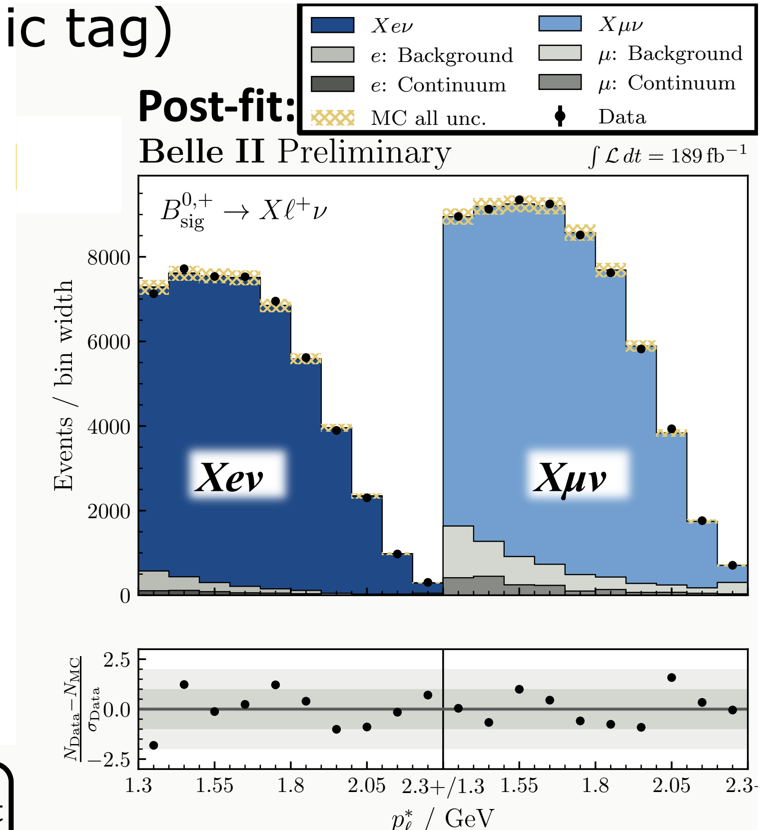
Detmold, Lehner, Meinel
arXiv:1503.01421

Test of e/μ universality (Belle II)

- Inclusive b→cl⁻ν analysis (hadronic tag)

$$R(X_{e/\mu}) = \frac{\mathcal{B}(B\to Xe\nu)}{\mathcal{B}(B\to X\mu\nu)}$$





$$R(X_{e/\mu})^{p^*_\ell>1.3\mathrm{GeV}} = 1.033 \pm 0.010^{\mathrm{stat}} \pm 0.020^{\mathrm{syst}}$$

- ➢ **Most precise LFU test in b→cl⁻ν to date**
  - ➢ precursor to an inclusive $B\to X\tau\nu$ / $B\to Xl\nu$ measurement

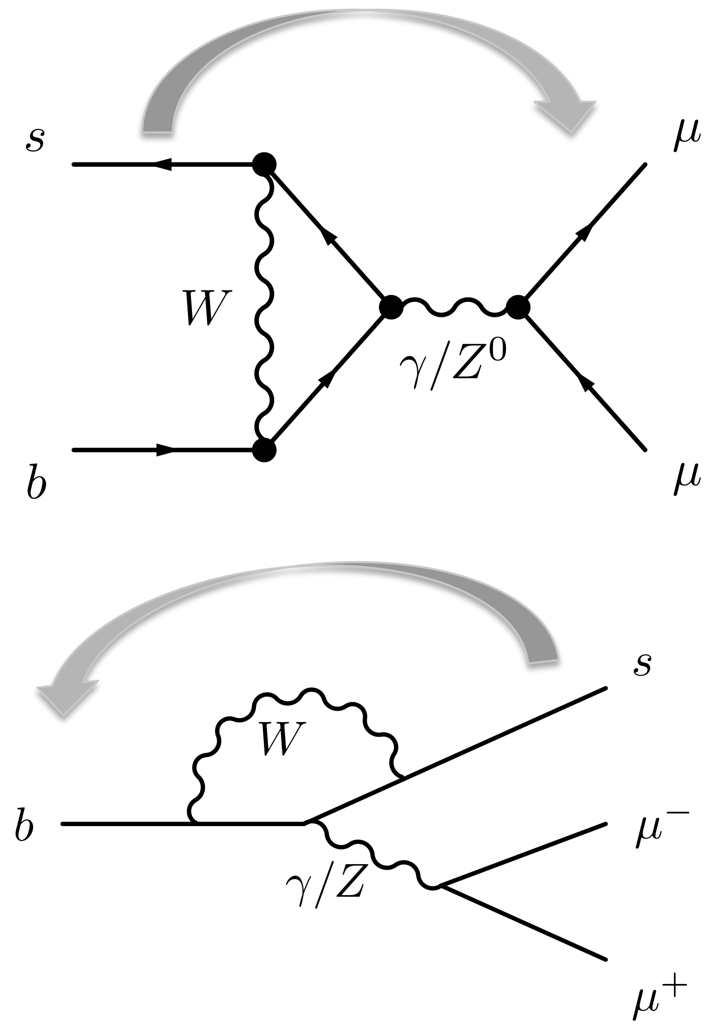
$b \to s l^+ l^-$

Rich laboratory:

1) Purely leptonic
2) Decay rates
3) Angular asymmetries
4) Ratio of decay rates

$B_s^0 \to \mu^+\mu^-$

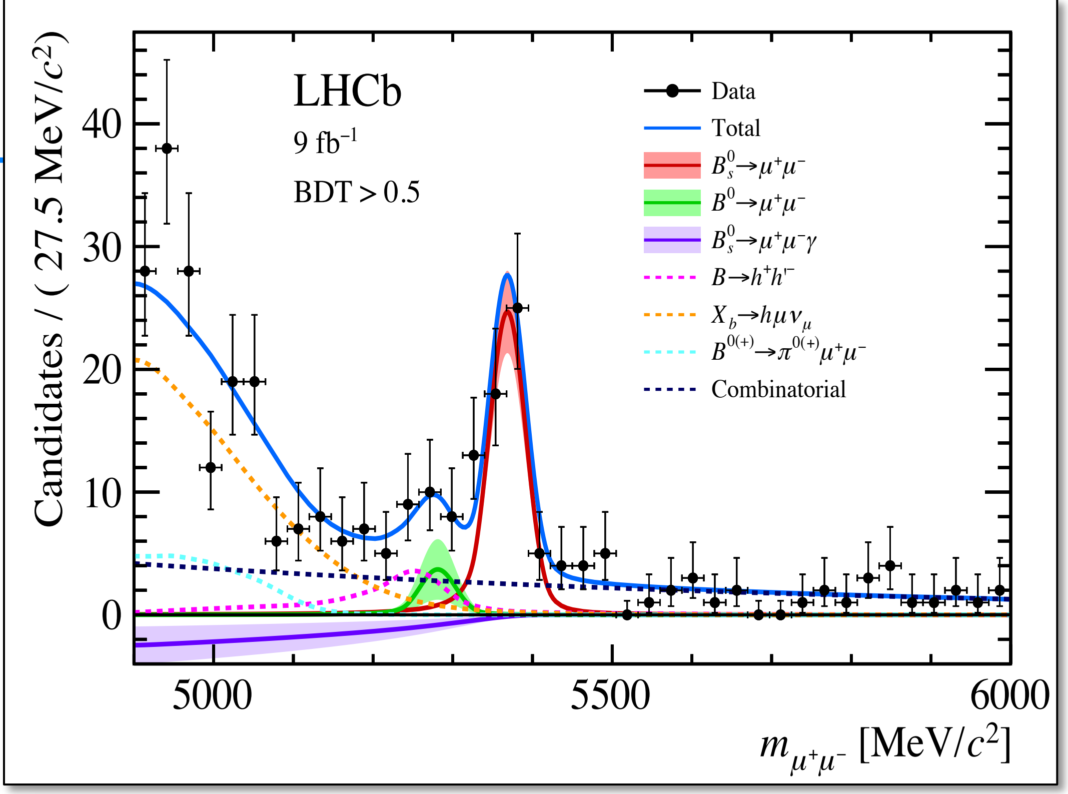
- Purely leptonic $b \to s l^+ l^-$



+ $B_s^0 \to e^+e^-$ (LHCb, arXiv:2003.03999)

+ $B_s^0 \to \tau^+\tau^-$ (LHCb, arXiv:1703.02508)

$B_s^0 \to \mu^+\mu^-$ (LHCb)



LHCb Coll. arXiv:2108.09284

Theory:

$$B(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$

$$B(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

Beneke, Bobeth, Szafron, arXiv:1908.07011

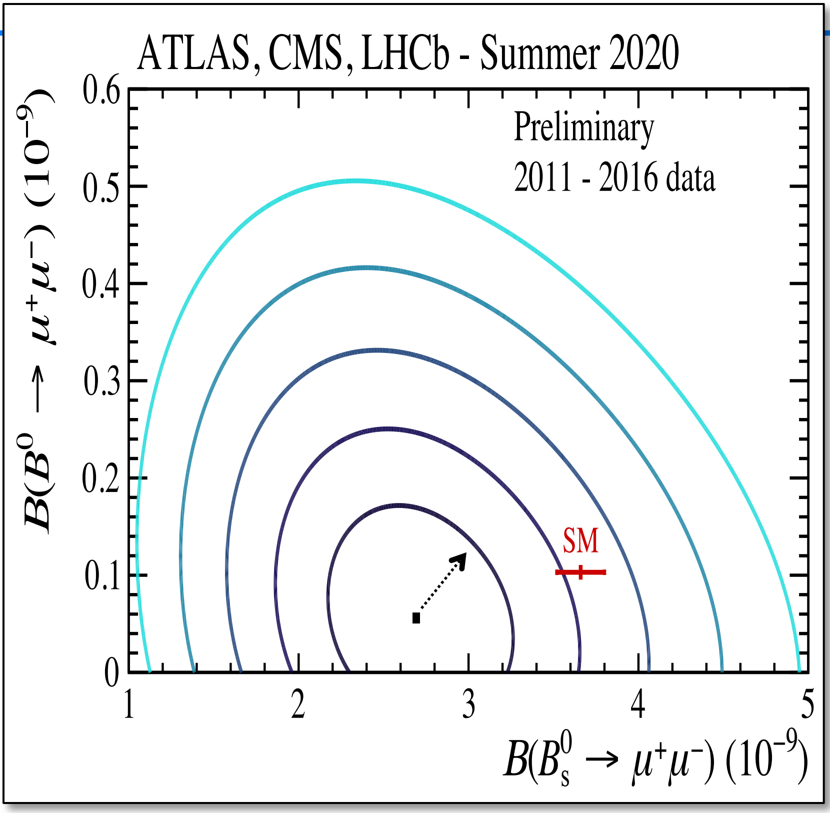
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}\right) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}$$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{m_{\mu\mu} > 4.9\,\mathrm{GeV}/c^2} < 2.0 \times 10^{-9}$$

$B_{(s)}^0 \to \mu^+\mu^-$ (2020)

- Including B^0:



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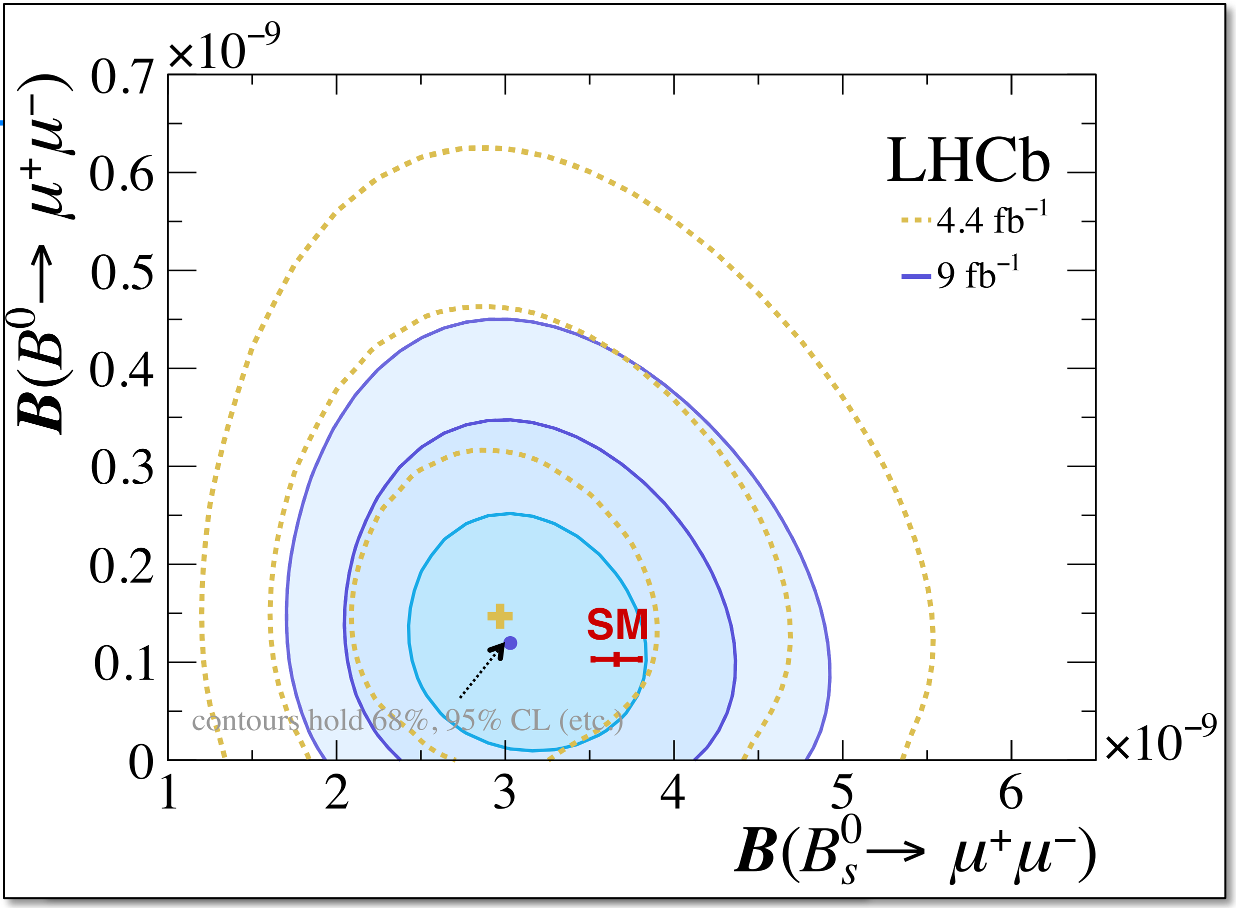


LHCb Coll. arXiv:2108.09284

- NB: new result from CMS at ICHEP not included here

- Relative production of B_s^0 wrt B^0 mesons, f_s/f_d :

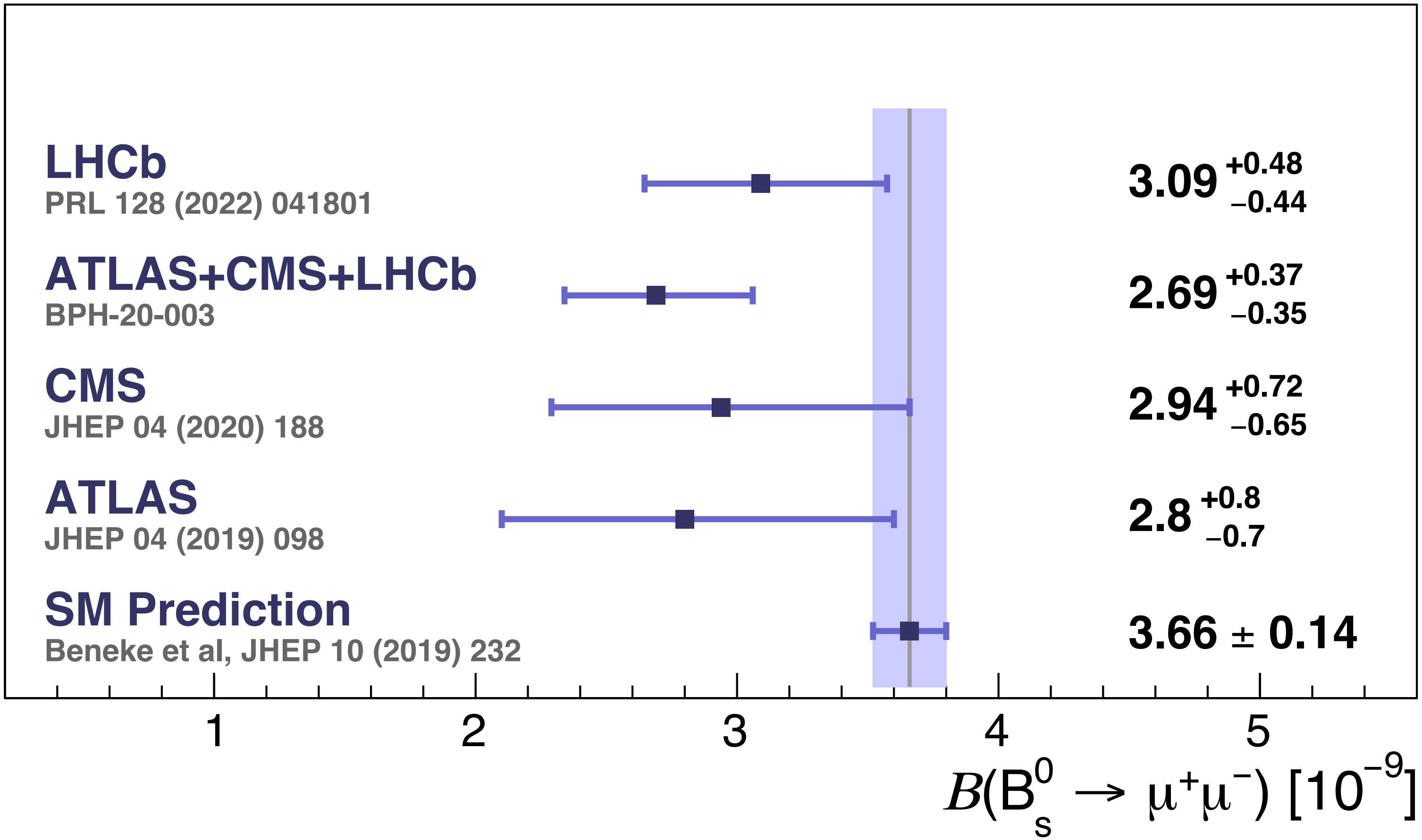
$f_s/f_d\,(7\,\text{TeV})$	$=$	0.2390 ± 0.0076
$f_s/f_d\,(8\,\text{TeV})$	$=$	0.2385 ± 0.0075
$f_s/f_d\,(13\,\text{TeV})$	$=$	0.2539 ± 0.0079

(Integrated, p_T [0.5,40] GeV/c, η [2.6,4])

$$f_s/f_d \quad (p_T, 7\,\text{TeV}) = (0.244 \pm 0.008) + ((-10.3 \pm 2.7) \times 10^{-4}) \cdot p_T$$
$$f_s/f_d \quad (p_T, 8\,\text{TeV}) = (0.240 \pm 0.008) + ((-\ 3.4 \pm 2.3) \times 10^{-4}) \cdot p_T$$
$$f_s/f_d \quad (p_T, 13\,\text{TeV}) = (0.263 \pm 0.008) + ((-17.6 \pm 2.1) \times 10^{-4}) \cdot p_T$$

LHCb Coll, arXiv:2103.06810

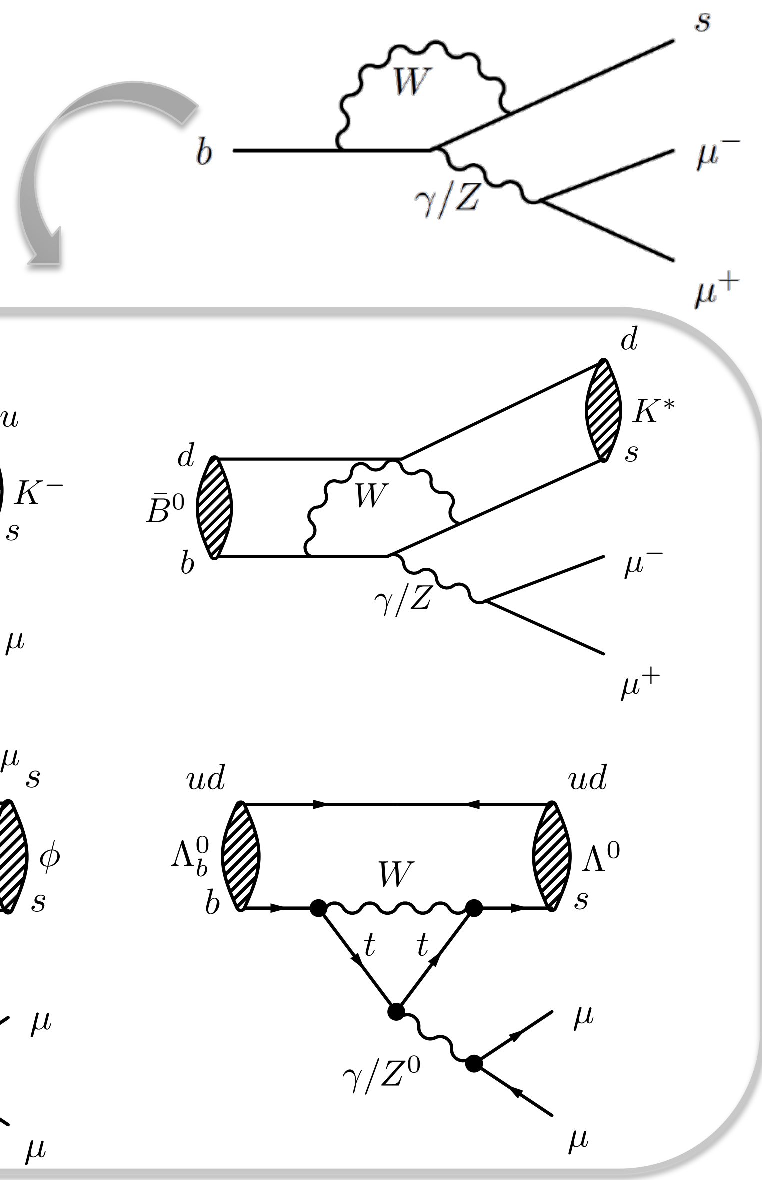
$B_s^0 \to \mu^+\mu^-$



From: D.Kovalskyi (CMS), ICHEP, 9 July 2022

Decay rates

- Study same process with different hadrons:



$b \rightarrow s l^+ l^-$

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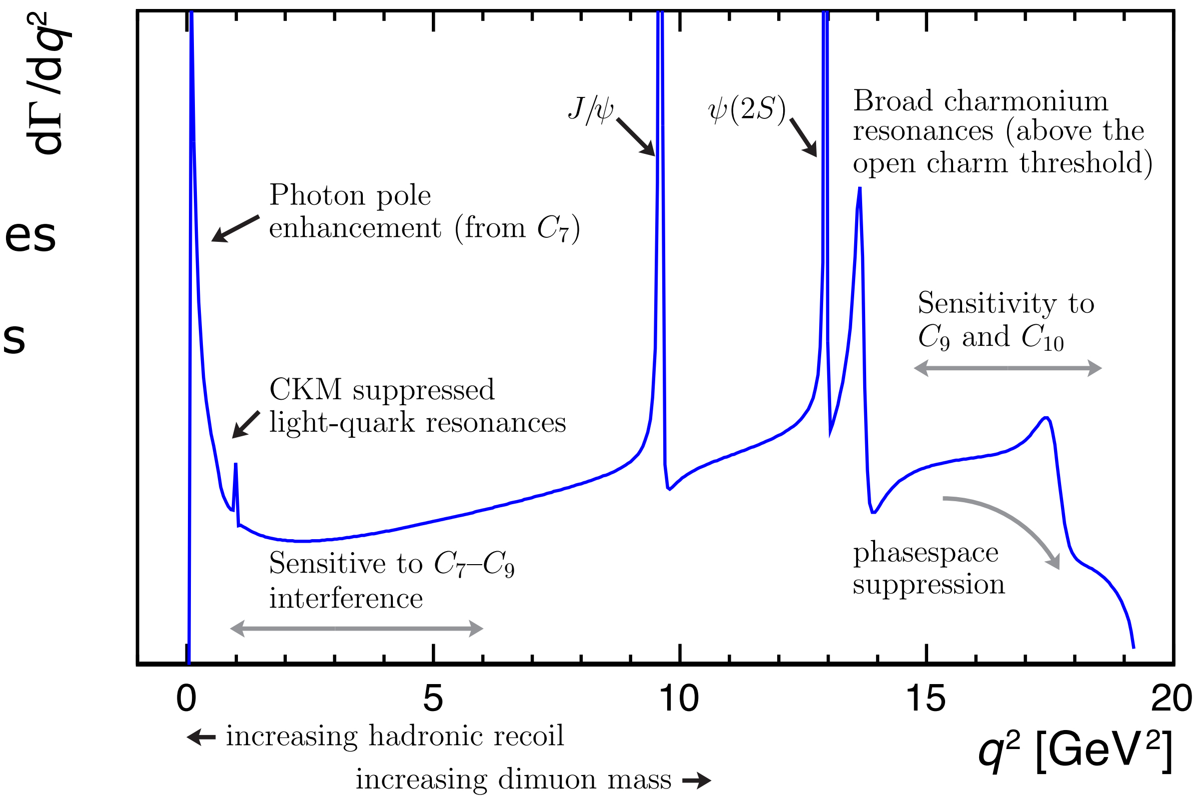
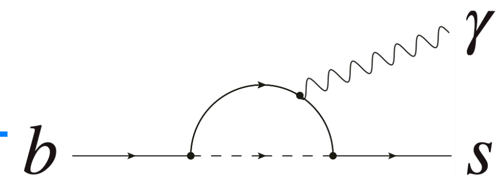
T.Blake et al. arXiv:1606.00916



b→sγ: Radiative decays



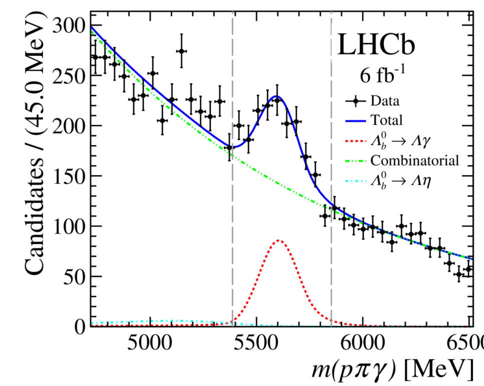
- Radiative decays are sensitive to $C_7^{(\prime)}$

$\Lambda_b{}^0 \to \Lambda\gamma$ (LHCb)

$$\Gamma(\theta_p) \propto 1 - \alpha_\gamma \alpha_\Lambda \cos\theta_p$$

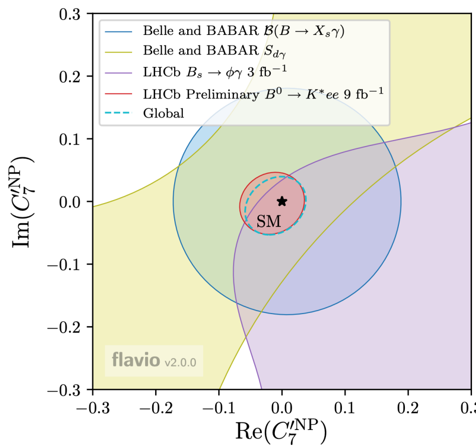
$$\alpha_\gamma = \frac{\gamma_L - \gamma_R}{\gamma_L + \gamma_R} \qquad \alpha_\gamma^{SM} = 1$$

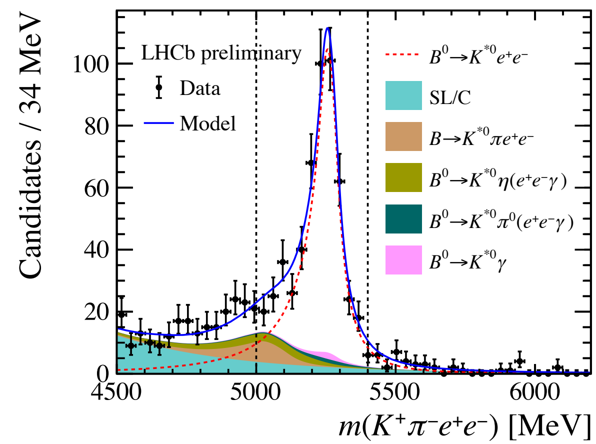
$$\alpha_\gamma = 0.82^{+0.17}_{-0.26}\ (\text{stat.})^{+0.04}_{-0.13}\ (\text{syst.})$$



LHCb Coll, arXiv:2111.10194

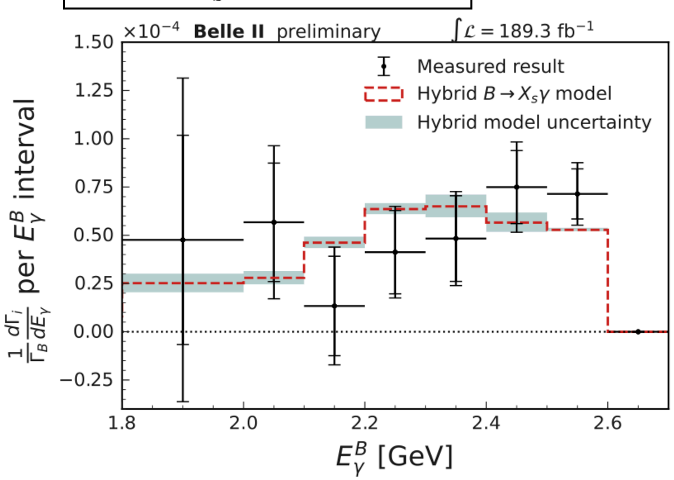
$B^0 \to K^{*0}\gamma\ (\to e^+e^-)$ (LHCb)





LHCb Coll, arXiv:2010.06011

$B \to X_s\gamma$ (Belle II)

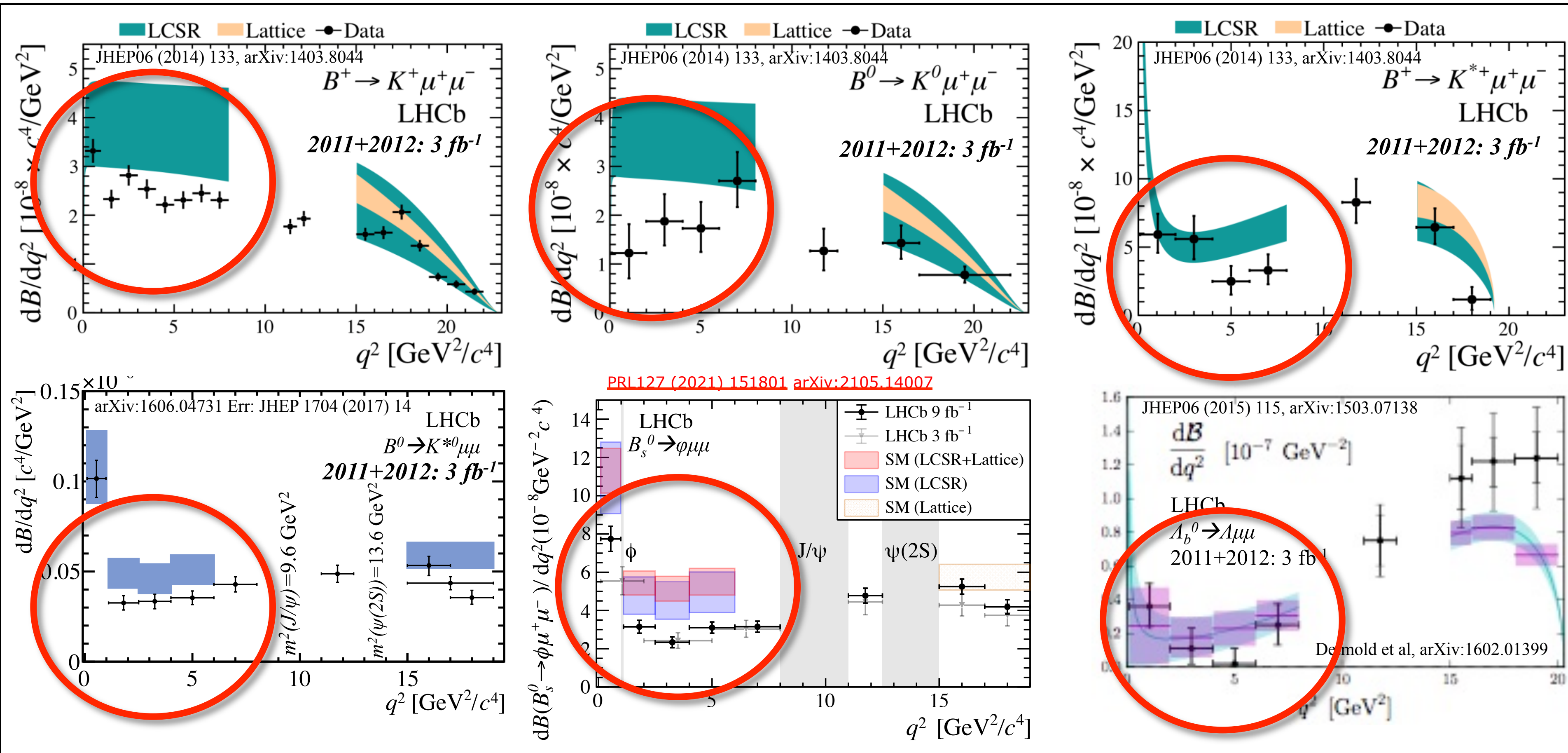


ICHEP, E.Ganiev, 9 July 2022

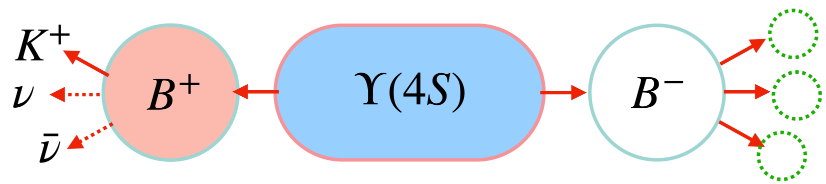
E_γ^B threshold, GeV	$\mathcal{B}(B \to X_s\gamma)(10^{-4})$
1.8	3.54 ± 0.78 (stat.) ± 0.83 (syst.)
2.0	3.06 ± 0.56 (stat.) ± 0.47 (syst.)

Decay rates (LHCb)

- Decay rate with muons in final state consistently low:

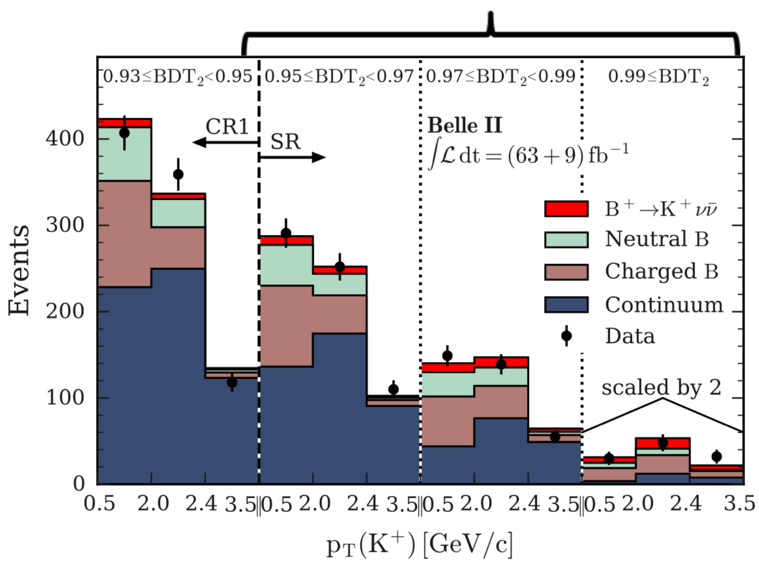


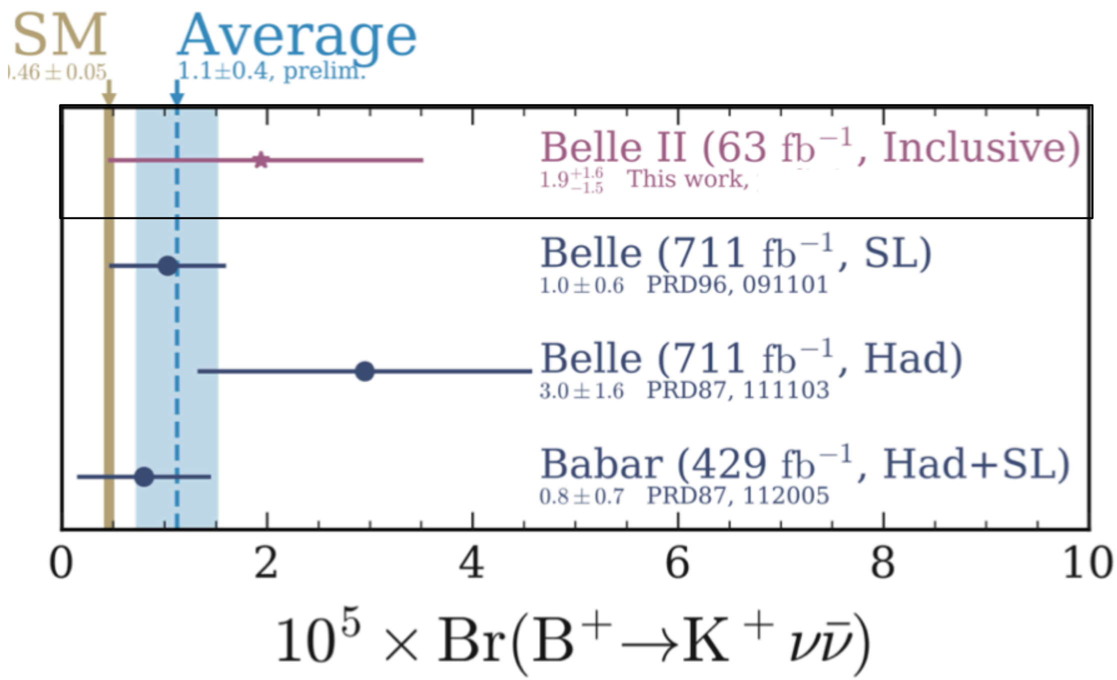
$B^+ \to K^+ \nu \nu$ (Belle II)



- Unique to Belle II
  - Connection to b→smm in eg. Descotes-Genon et al PLB 809 (2020) 135769
- Inclusive tag based on event topology
- Compatible with SM at 1.0σ

$$\mathrm{BF}(B^+ \to K^+ \nu\bar{\nu}) = (1.9^{+1.6}_{-1.5}) \times 10^{-5}$$



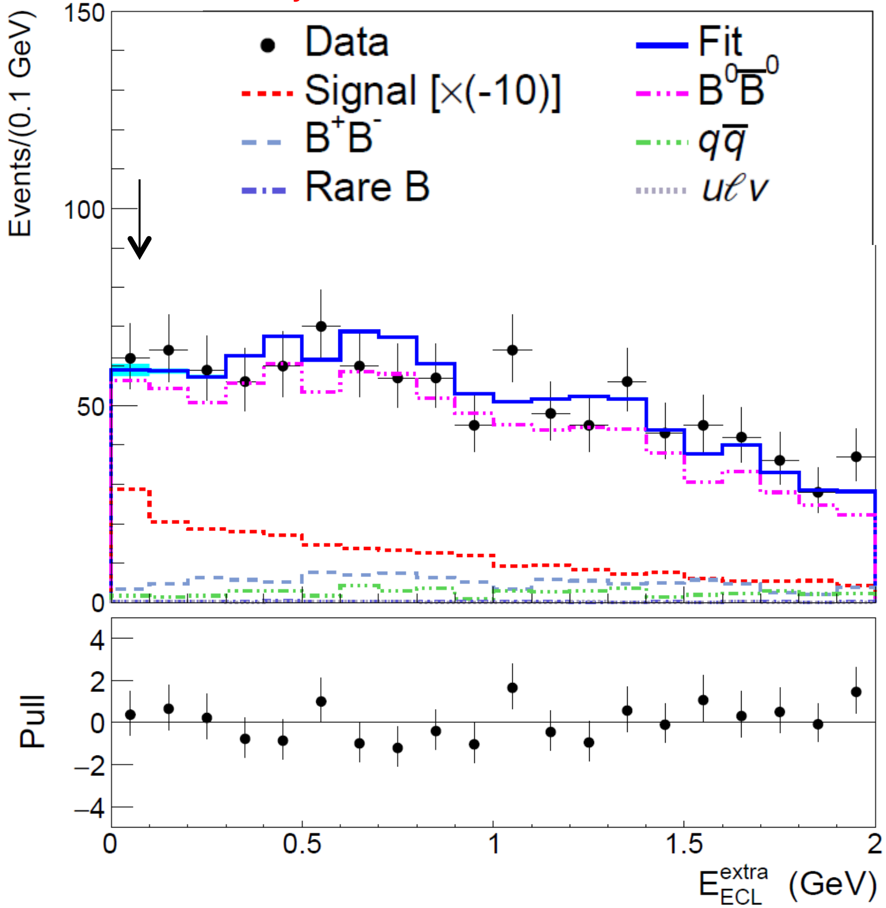


Belle II Coll, arXiv:2104.12624

$B^0 \to K^{0*}\tau^+\tau^-$ (Belle)

- BR can be significantly enhanced

Preliminary result



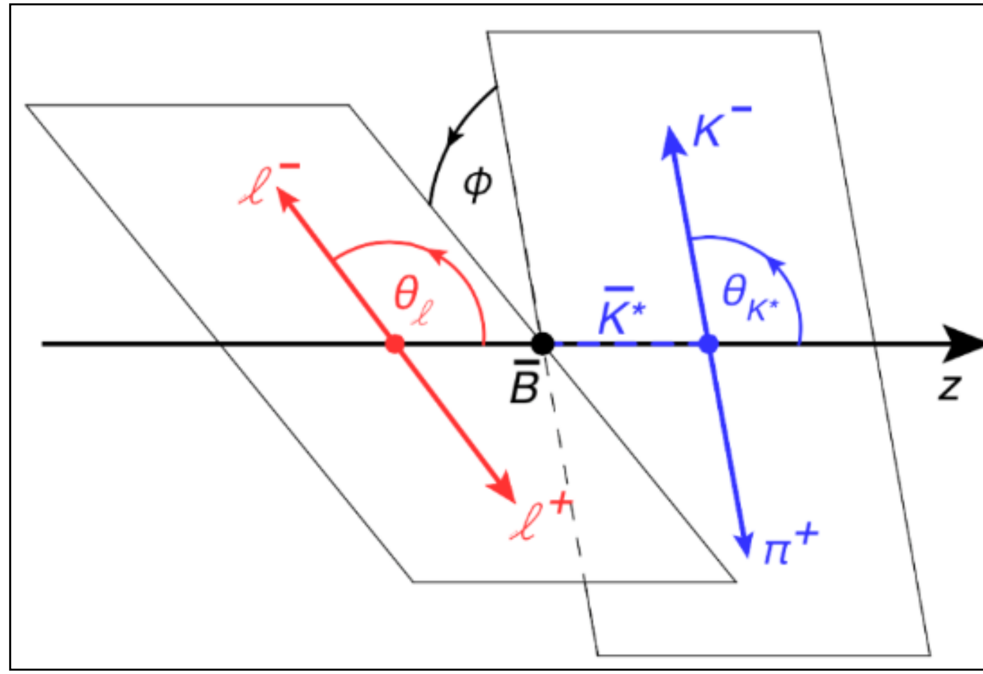
- E_{ECL}^{extra} = 0 for signal → $E_{ECL}^{extra} < 0.2$ GeV
- $N_{sig} = -4.9 \pm 6.0$

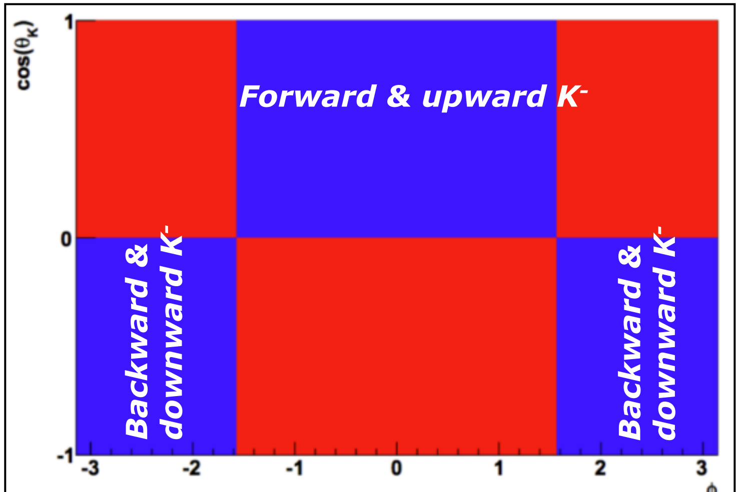
$$\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 2.0 \times 10^{-3} \text{ at } 90\%$$

K.Kang, ICHEP, 9 July 2022
Belle Coll. arXiv:2110.03871

Angular asymmetries

P_5':

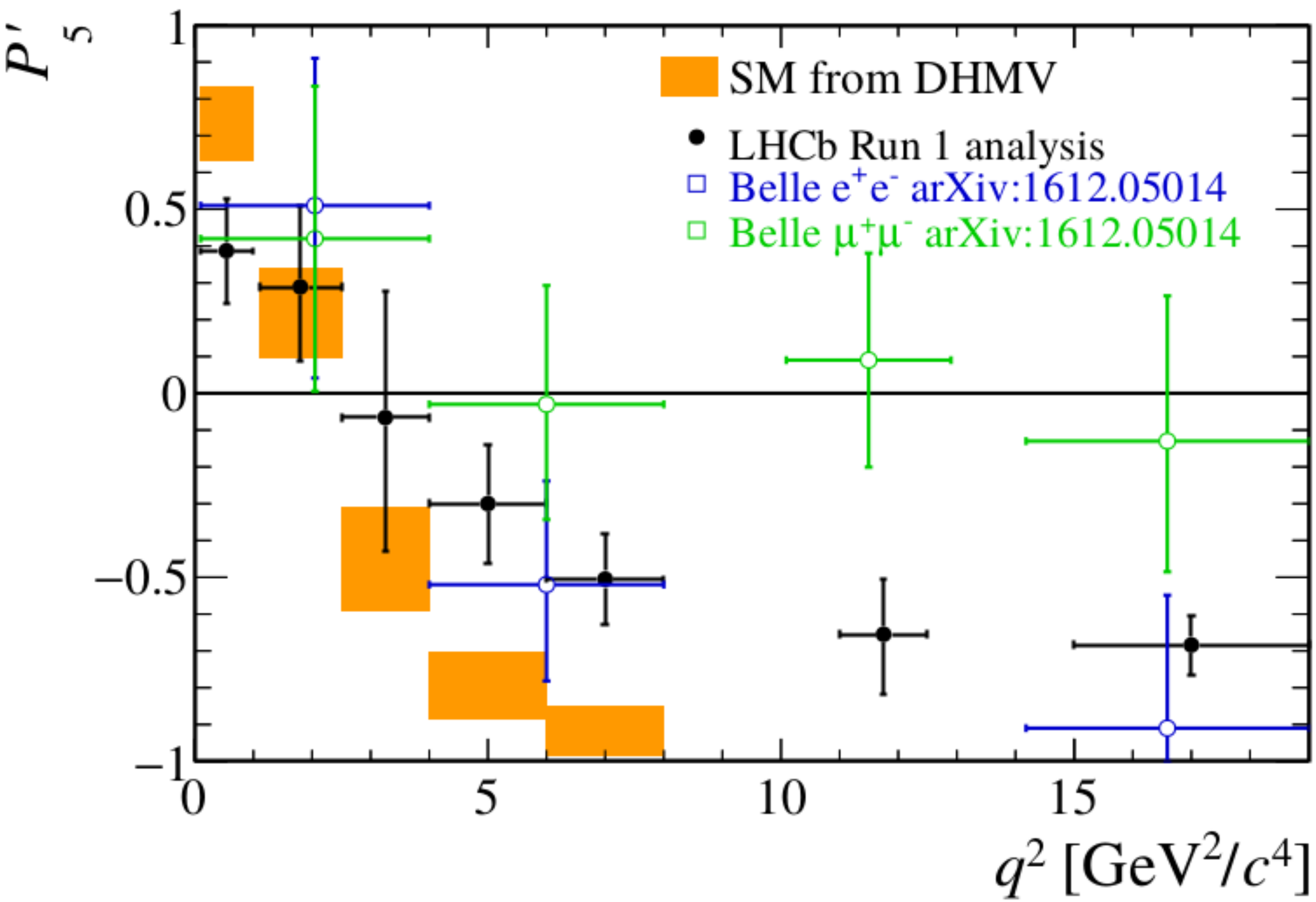




Counting S_5: blue minus red

Angular asymmetries (Belle)

- Interesting to compare angular asymmetries for μ and e

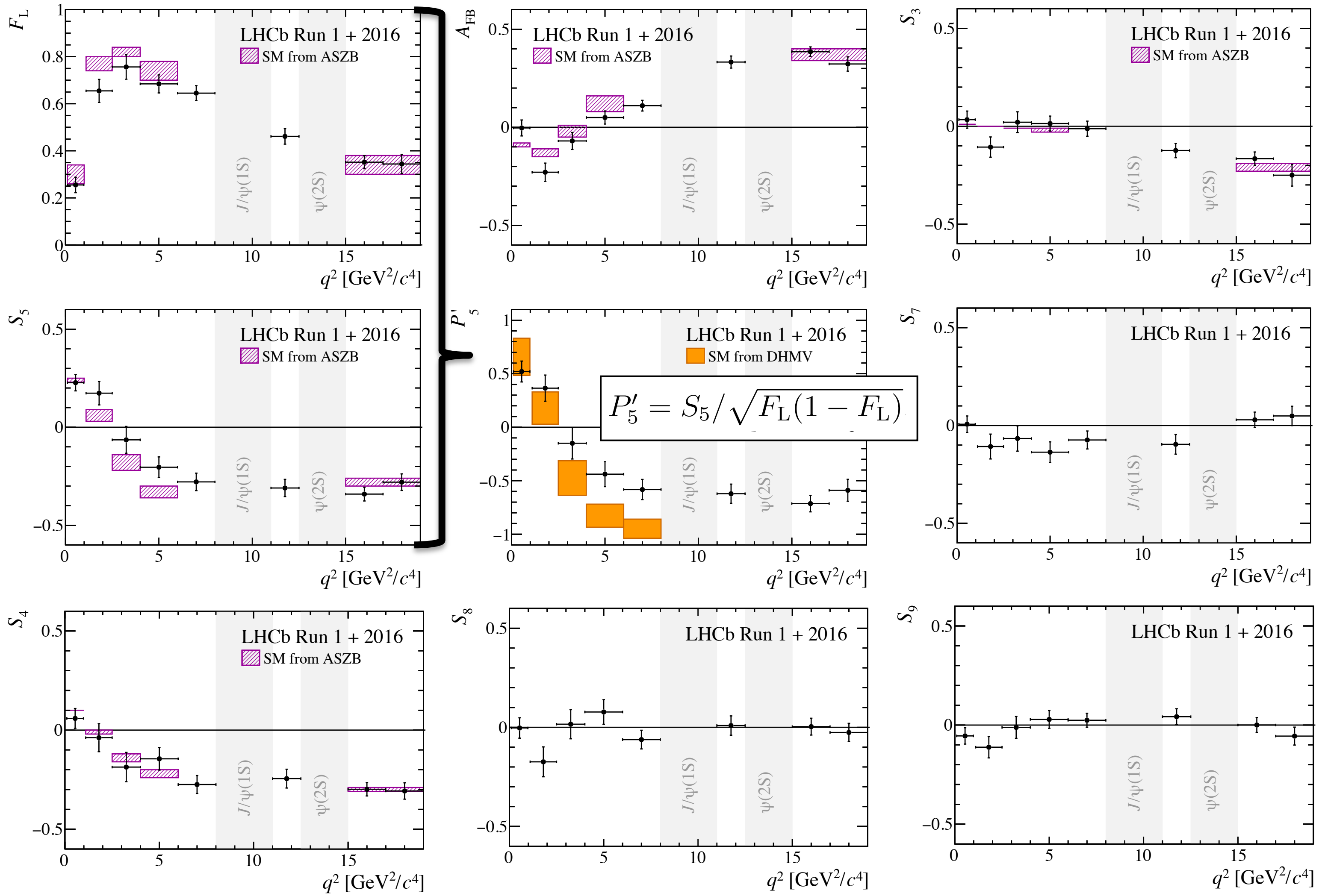


LHCb, arXiv:1512.04442

$B^0 \to K^{0*}\mu^+\mu^-$: more than just P_5'

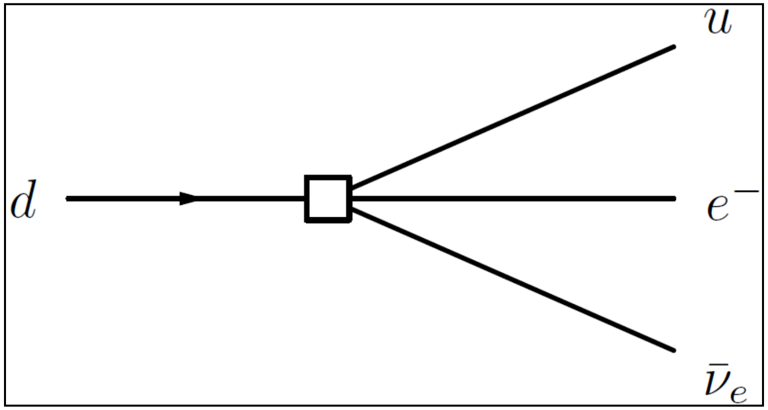
- Many measurements:

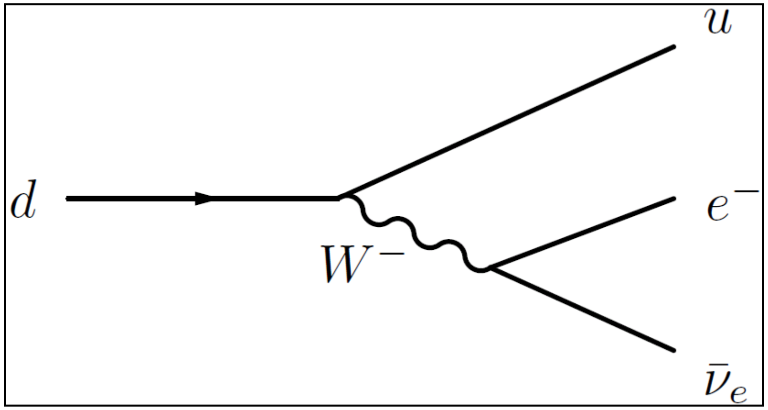
LHCb Coll, arXiv:2003.04831



Intermezzo: Effective couplings

- Historical example



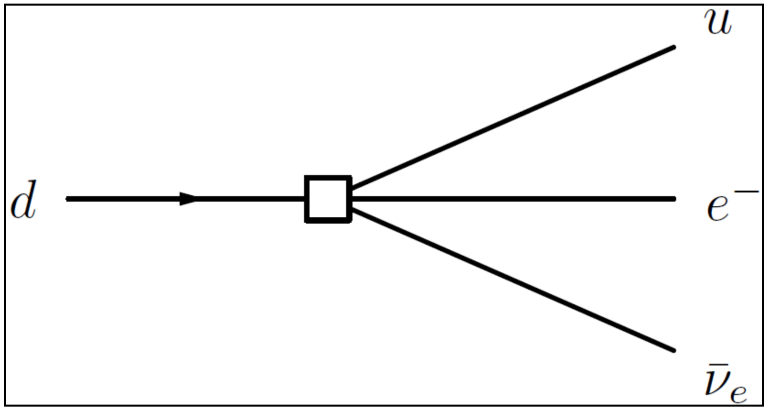


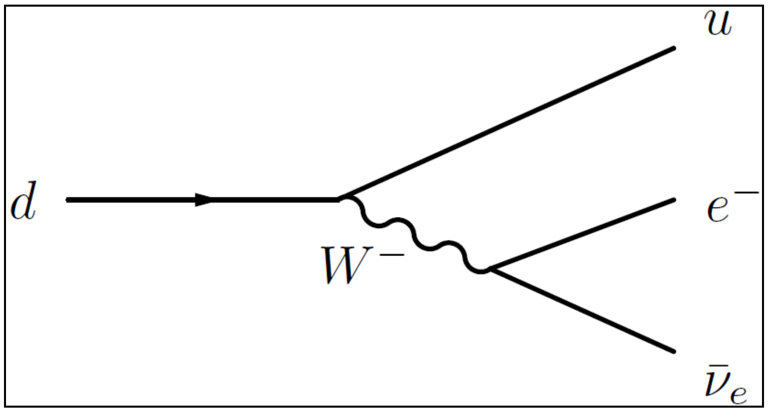
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

- Both are correct, depending on the energy scale you consider

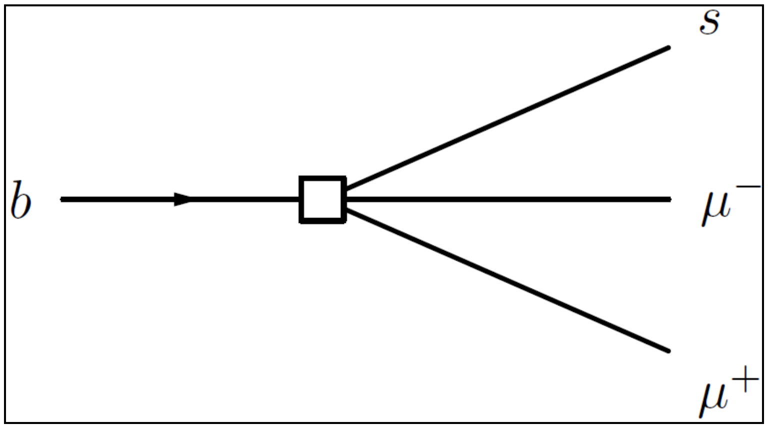
Intermezzo: Effective couplings

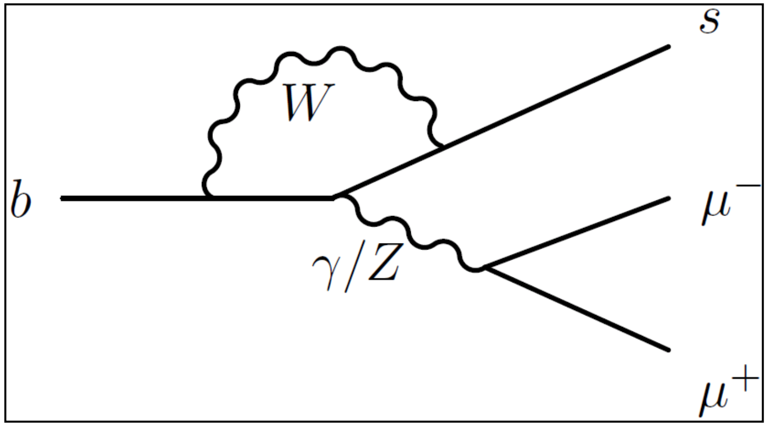
- Historical example





- Analog: *Flavour-changing neutral current*





Intermezzo: Effective couplings

- Effective coupling can be of various "kinds"
  - Vector coupling: C_9
  - Axial coupling: C_{10}
  - Left-handed coupling (V-A): C_9-C_{10}
  - Right-handed (to quarks): C_9', C_{10}', …
  - …

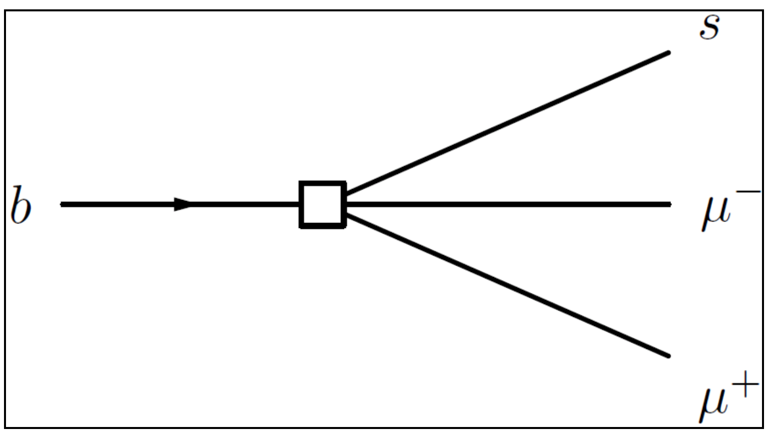
$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{\text{CKM}} \sum_i C_i(\mu) Q_i$$

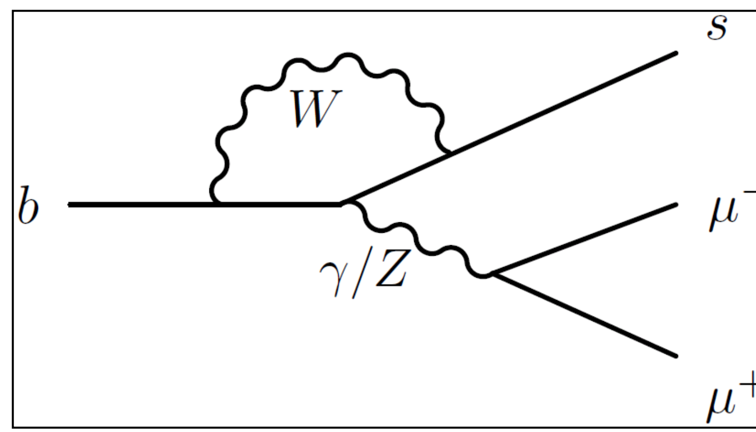
See e.g. Buras & Fleischer, hep-ph/9704376

Semi–Leptonic Operators (fig. 11f):

$Q_{9V} = (\bar{s}b)_{V-A}(\bar{\mu}\mu)_V \qquad Q_{10A} = (\bar{s}b)_{V-A}(\bar{\mu}\mu)_A$

- Analog: *Flavour-changing neutral current*





Intermezzo: Effective couplings

- C_7 (photon), C_9 (vector) and C_{10} (axial) couplings hide everywhere:

$$A_\perp^{L,R} \propto (C_9^{eff} + C_9^{eff\prime}) \mp (C_{10}^{eff} + C_{10}^{eff\prime}) \frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(C_7^{eff} + C_7^{eff\prime})T_1(q^2)]$$

$$A_\parallel^{L,R} \propto [(C_9^{eff} - C_9^{eff\prime}) \mp (C_{10}^{eff} - C_{10}^{eff\prime}) \frac{A_1(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(C_7^{eff} - C_7^{eff\prime})T_2(q^2)]$$

$$A_0^{L,R} \propto [(C_9^{eff} - C_9^{eff\prime}) \mp (C_{10}^{eff} - C_{10}^{eff\prime})] \times [(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*} A_1(q^2) - \lambda \frac{A_2(q^2)}{m_B + m_{K^*}})] + 2m_b(C_7^{eff} - C_7^{eff\prime})[(m_B^2 + 3m_{K^*}^2 - q^2)T_2(q^2) - \frac{\lambda}{m_B^2 - m_{K^*}^2 T_3(q^2)}]$$

$$F_L = \frac{A_0^2}{A_\parallel^2 + A_\perp^2 + A_0^2}$$

$$S_3 = \frac{A_\perp^{L2} - A_\parallel^{L2}}{A_\perp^{L2} + A_\parallel^{L2} + A_0^{L2}} + L \to R$$

$$S_4 = \frac{\Re(A_0^{L*} A_\parallel^L)}{|A_0^L|^2 |A_\parallel^L|^2 + |A_0^L|^2} + L \to R$$

$$S_5 = \frac{\Re(A_0^{L*} A_\perp^L)}{|A_0^L|^2 + A_\perp^L|^2 + |A_0^L|^2} - L \to R$$

$$S_6 = \frac{\Re(A_\perp^{L*} A_\parallel^L)}{|A_\perp^L|^2 + |A_\parallel^L|^2 + |A_0^L|^2} - L \to R = \frac{4}{3} A_{FB}$$

$$S_7 = \frac{\Im(A_0^{L*} A_\parallel^L)}{|A_0^L|^2 + |A_\parallel^L|^2 + |A_0^L|^2} + L \to R$$

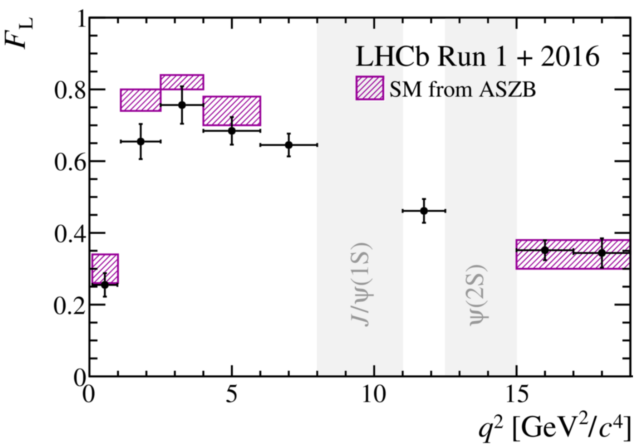
$$S_8 = \frac{\Im(A_0^{L*} A_\perp^L)}{|A_0^L|^2 + |A_\parallel^L|^2 + |A_0^L|^2} + L \to R$$

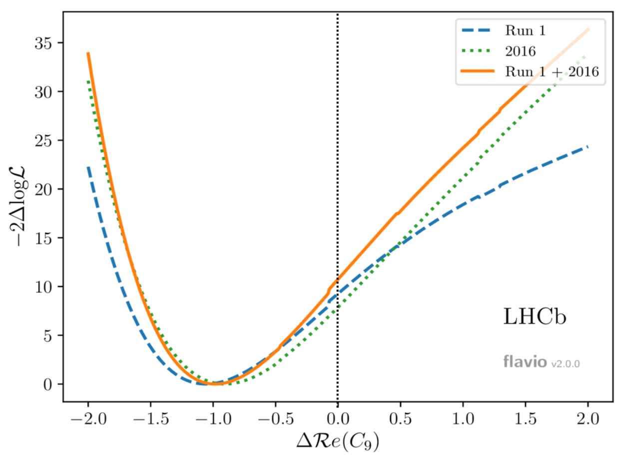
$$S_9 = \frac{\Im(A_\perp^{L*} A_\parallel^L)}{|A_\perp^L|^2 + |A_\parallel^L|^2 + |A_0^L|^2} - L \to R$$

$$\frac{1}{\Gamma} \frac{d^3(\Gamma + \bar{\Gamma})}{d\cos\theta_\ell \, d\cos\theta_K \, d\phi} = \frac{9}{32\pi} \Big[\frac{3}{4}(1 - F_L)\sin^2\theta_K + F_L \cos^2\theta_K + \frac{1}{4}(1 - F_L)\sin^2\theta_K \cos 2\theta_\ell$$
$$- F_L \cos^2\theta_K \cos 2\theta_\ell +$$
$$S_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi +$$
$$S_5 \sin 2\theta_K \sin\theta_\ell \cos\phi + S_6^s \sin^2\theta_K \cos\theta_\ell +$$
$$S_7 \sin 2\theta_K \sin\theta_\ell \sin\phi +$$
$$S_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + S_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \Big]$$

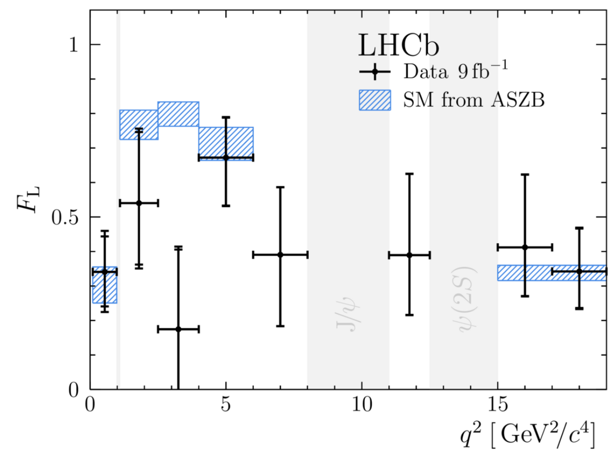
Coherent pattern

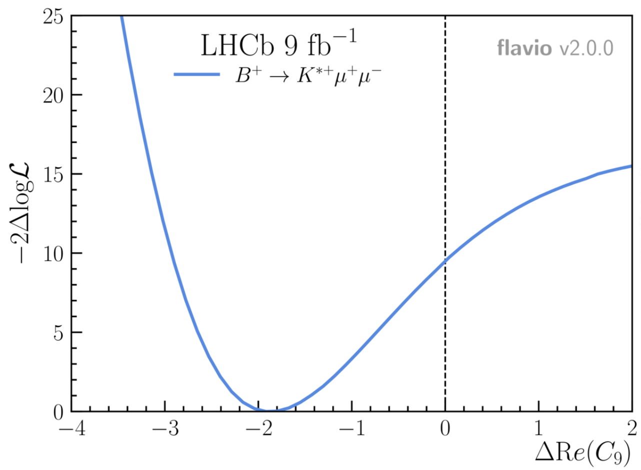
arXiv:2003.04831: $B^0 \to K^{*0}\mu^+\mu^-$



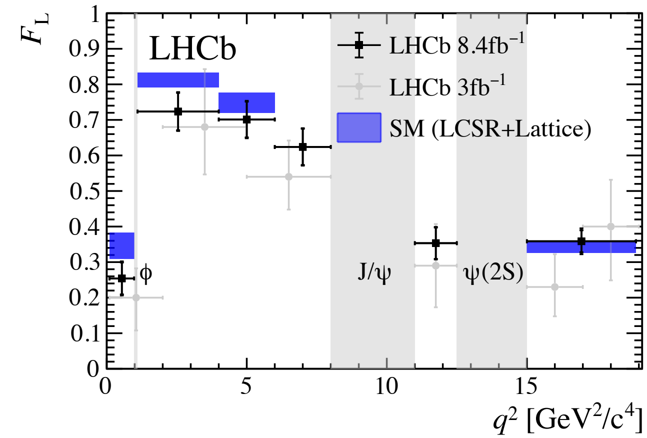


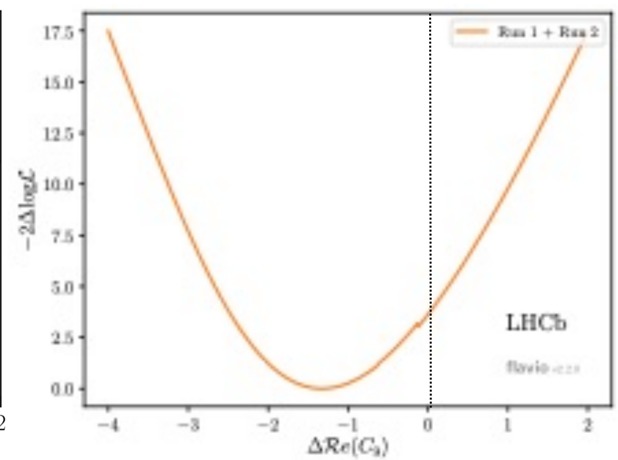
arXiv:2012.13241: $B^+ \to K^{*+}\mu^+\mu^-$

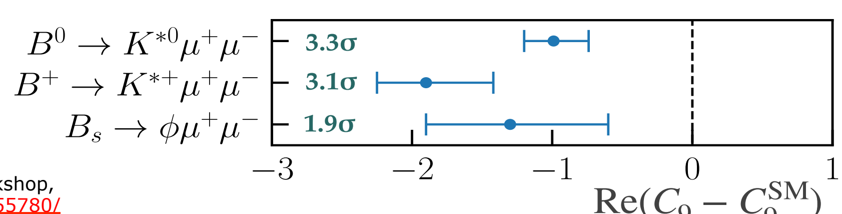




arXiv:2107.13428: $B^0_s \to \phi\mu^+\mu^-$



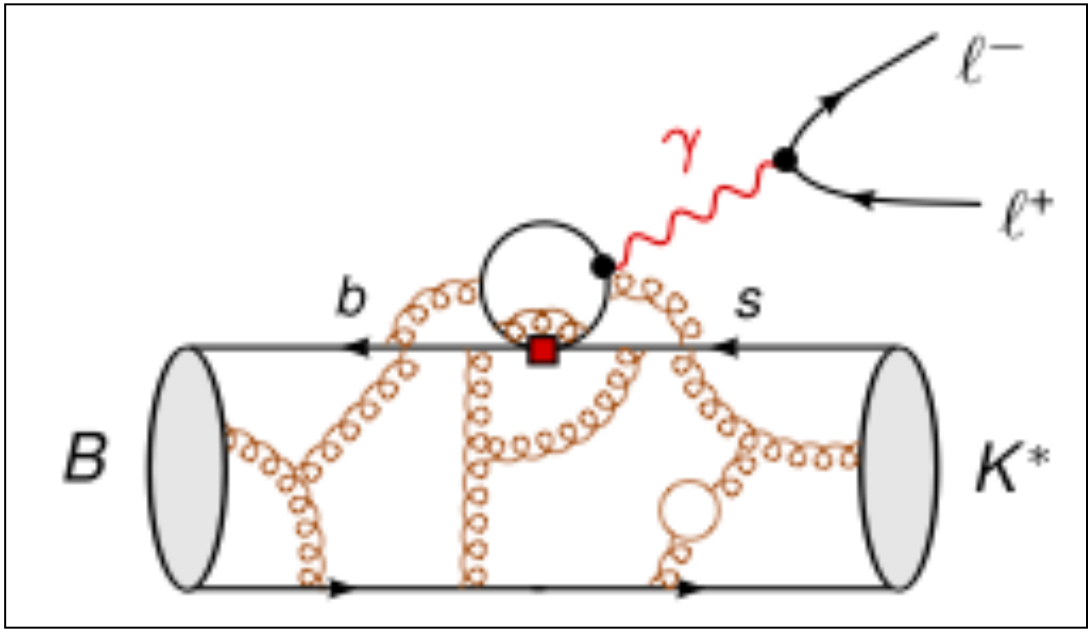


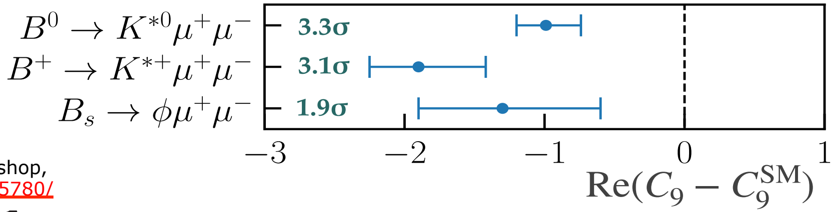


From: Martino Borsato, Flavour Anomaly Workshop, 20 Oct 2021, https://indico.cern.ch/event/1055780/

Coherent pattern

- Charm loop effects could also cause a shift in C_9



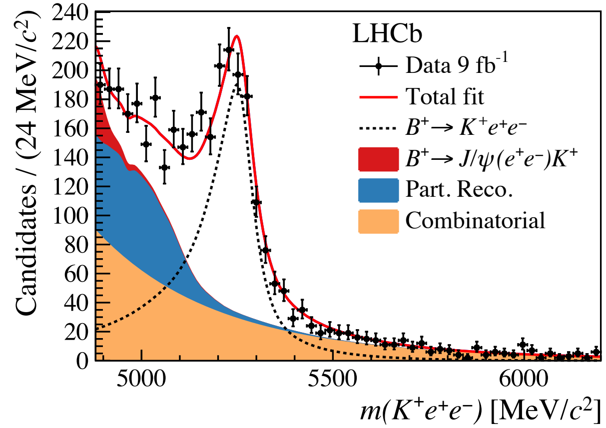


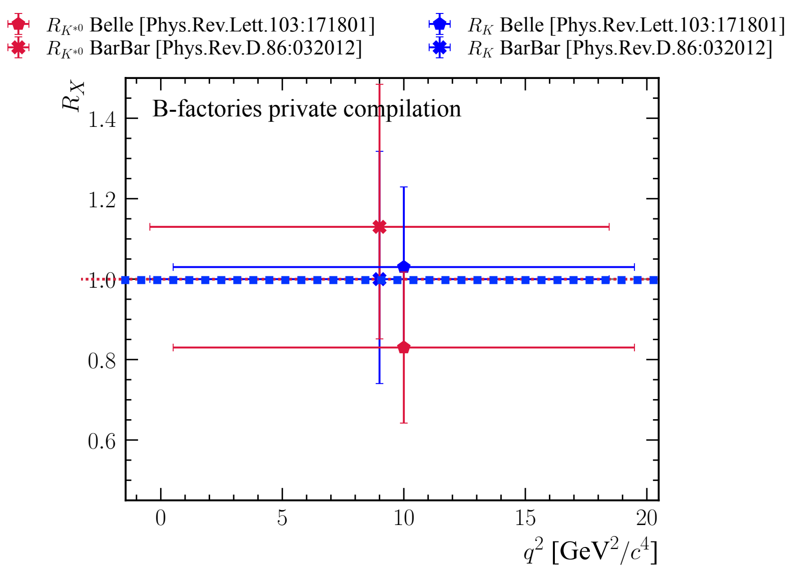
From: Martino Borsato, Flavour Anomaly Workshop, 20 Oct 2021, https://indico.cern.ch/event/1055780/

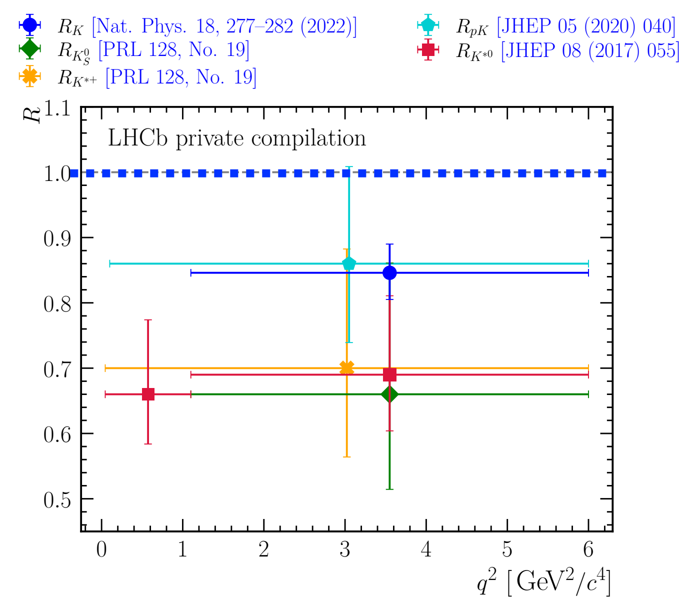
Ratio of decay rates

$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+ \mu^-))} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+ e^+ e^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+ e^-))}$$

- Theoretically "clean"
- Experimentally
  - Signal yields
  - Backgrounds
  - Electron reconstruction
  - Efficiencies cancel in ratio
  - Belle II: good electron reconstruction
  - LHCb: large B sample

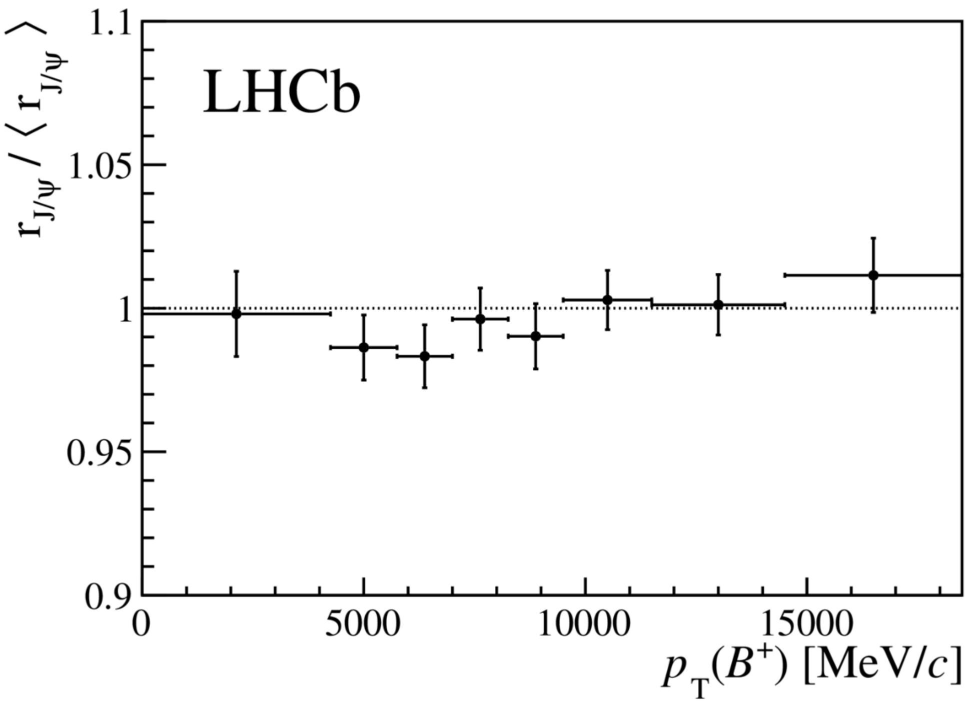


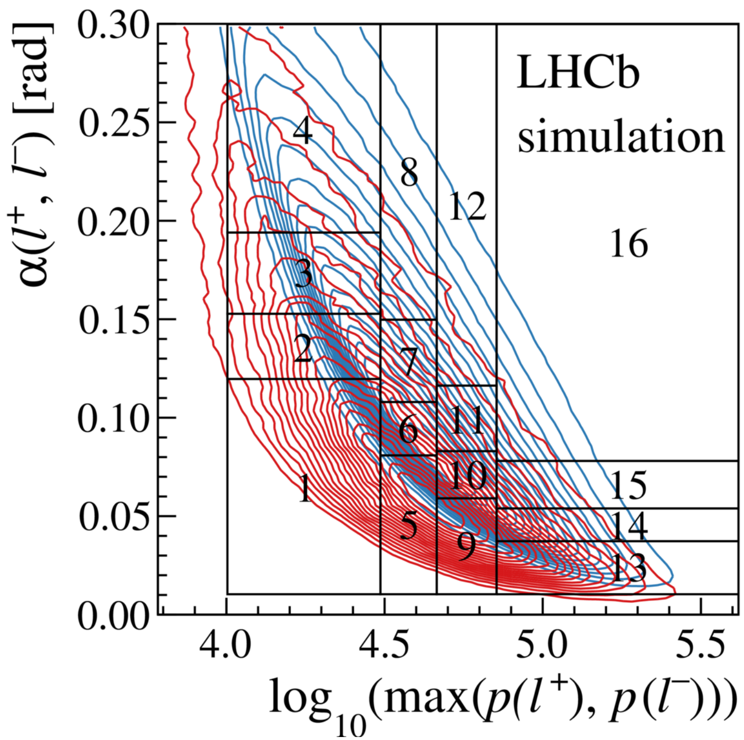




$r_{J/\psi}$ (LHCb)

- Test efficiencies are understood in all kinematic regions by checking $r_{J/\psi}$ is flat
- Flatness of $r_{J/\psi}$ 2D plots gives confidence that efficiencies are understood

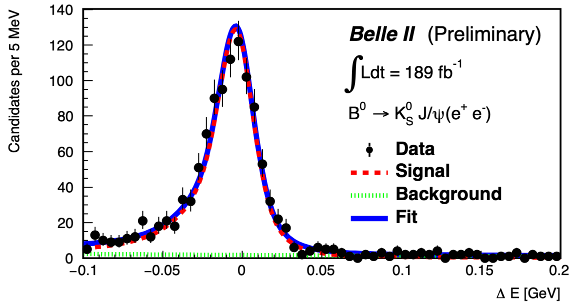


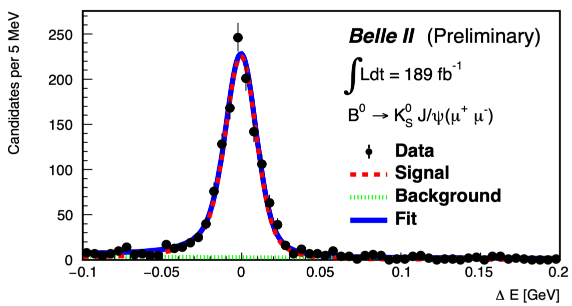


$$r_{J/\psi} = 0.981 \pm 0.020\ (\mathrm{stat} + \mathrm{syst})$$

LHCb Coll, arXiv:2103.11769

$r_{J/\psi}$ (Belle II)

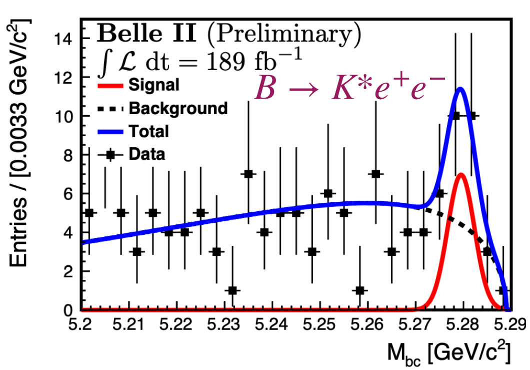


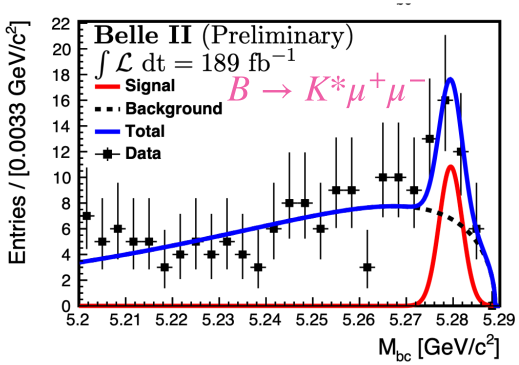


Observable	Belle II	Belle (2021)
$R_{K^+}(J/\psi)$	$1.009 \pm 0.022 \pm 0.008$	$0.994 \pm 0.011 \pm 0.010$
$R_{K^0_S}(J/\psi)$	$1.042 \pm 0.042 \pm 0.008$	$0.993 \pm 0.015 \pm 0.010$

ICHEP, 9 Jul 2022, E. Ganiev

- First $B \to K^* l^+ l^-$ events being collected
  - Belle II can provide independent check of $R_{K(*)}$ anomalies with few ab^{-1}





Belle II Coll, arXiv:2206.05946

Decay	Belle II (10^{-6})	PDG (10^{-6})
$B \to K^* e^+ e^-$	$1.42 \pm 0.48 \pm 0.09$	1.19 ± 0.20
$B \to K^* \mu^+ \mu^-$	$1.19 \pm 0.31^{+0.08}_{-0.07}$	1.06 ± 0.09

Analyses – where are we at LHCb ?

Analysis	Run 1	Run 2	
	2011-2012	2015-2016	2017-2018
$B_{(s)} \to \mu\mu$	✔	✔	✔
$B^0 \to K^{0*}\mu\mu$ (ang)	✔	✔	
$B^+_{/(s)} \to K^{*+}/\phi\mu\mu$ (ang)	✔	✔	✔
R_K	✔	✔	✔
R_{K*} (R_X)	✔		
R_{pK}	✔	✔	
$R_{KS,RK*+}$	✔	✔	✔
$R_{\phi,K\pi\pi,\pi,\Lambda}$			
R(D*)	✔		
R(D)			
$R(\Lambda_c)$	✔	✔	✔
+ many others	...	...	...
...	...	...	...

- We are working on a unified analysis of $B^+ \to K^+ l^+ l^-$ and $B^0 \to K^{*0} l^+ l^-$ decay ratios with electron and muon final states
  - This will provide the final Run-1 and 2 results on these key b→sll LFNU observables
  - Important checks in the absence of competitive results from other experiments.
- These efforts are leading to a deeper understanding of our LFNU measurements. This understanding will be reflected in our final results

Outline

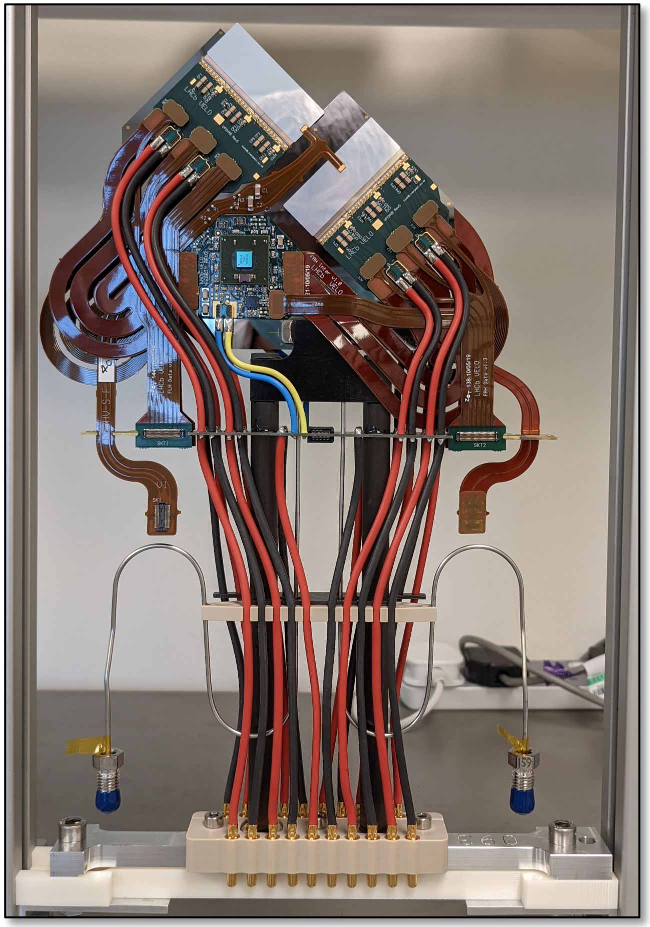
- CC: $b \to c l^- \nu$
  - $R(D^{(*)})$
- FCNC: $b \to s l^+ l^-$
  - $B_s^0 \to \mu^+ \mu^-$
  - Decay rates
  - Angular analyses
  - Lepton flavour ratios
- Effective couplings
- Prospects
  - Belle-II
  - LHCb Upgrade 1
  - LHCb Upgrade 2

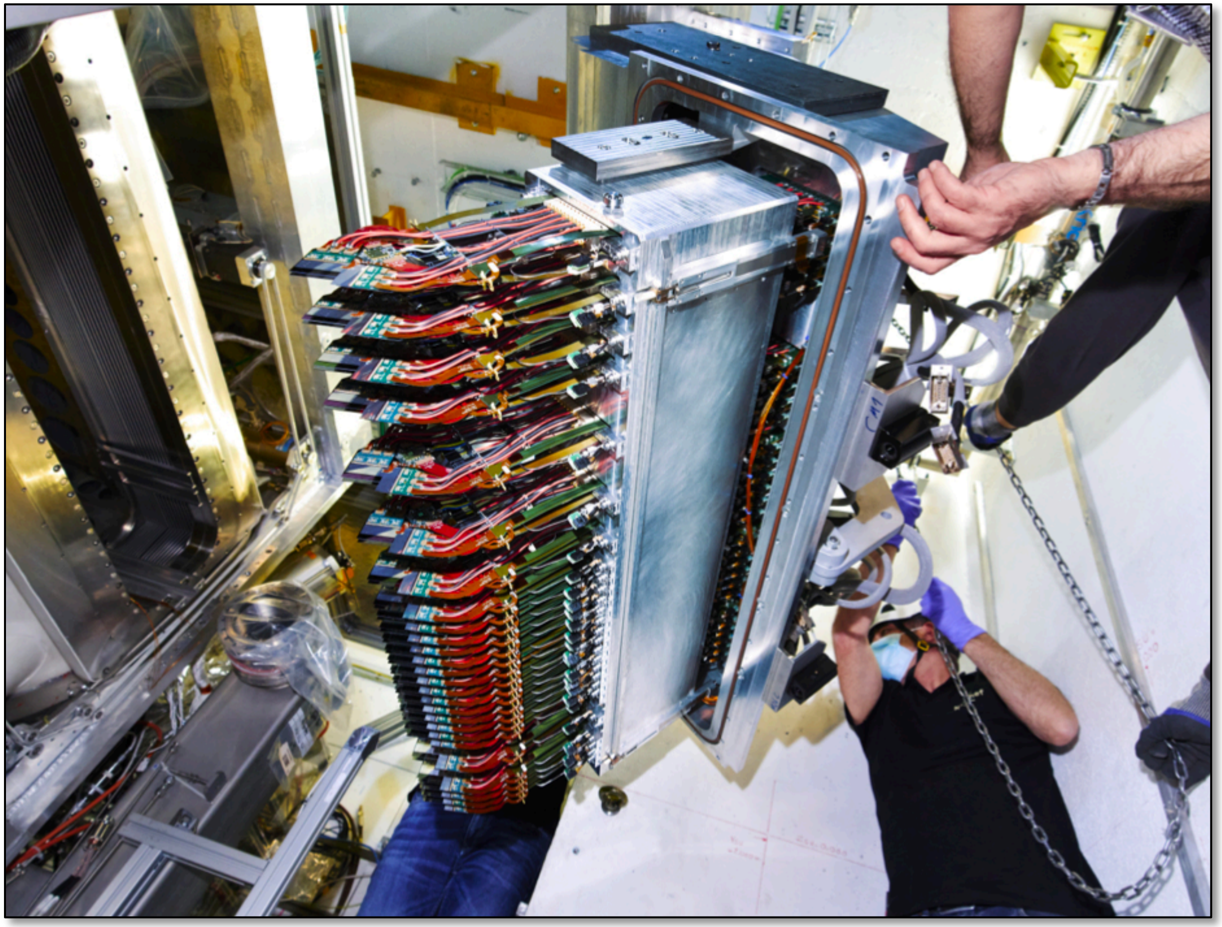
Future Plans

2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035+
		Run III						Run IV						Run V
LS2						**LS3**						**LS4**		
LHCb **40 MHz** **UPGRADE I**			$L = 2 \times 10^{33}$		**LHCb** **Consolidate**				$L = 2 \times 10^{33}$ $50\ fb^{-1}$			**LHCb** **UPGRADE II**		$L=1\text{-}2 \times 10^{34}$ $300\ fb^{-1}$
ATLAS **Phase I Upgr**			$L = 2 \times 10^{34}$		**ATLAS** **Phase II UPGRADE**				**HL-LHC** $L = 5 \times 10^{34}$					**HL-LHC** $L = 5 \times 10^{34}$
CMS **Phase I Upgr**			$300\ fb^{-1}$		**CMS** **Phase II UPGRADE**									$3000\ fb^{-1}$
Belle II		$L = 3 \times 10^{35}$				$7\ ab^{-1}$					$L = 6 \times 10^{35}$		$50\ ab^{-1}$	

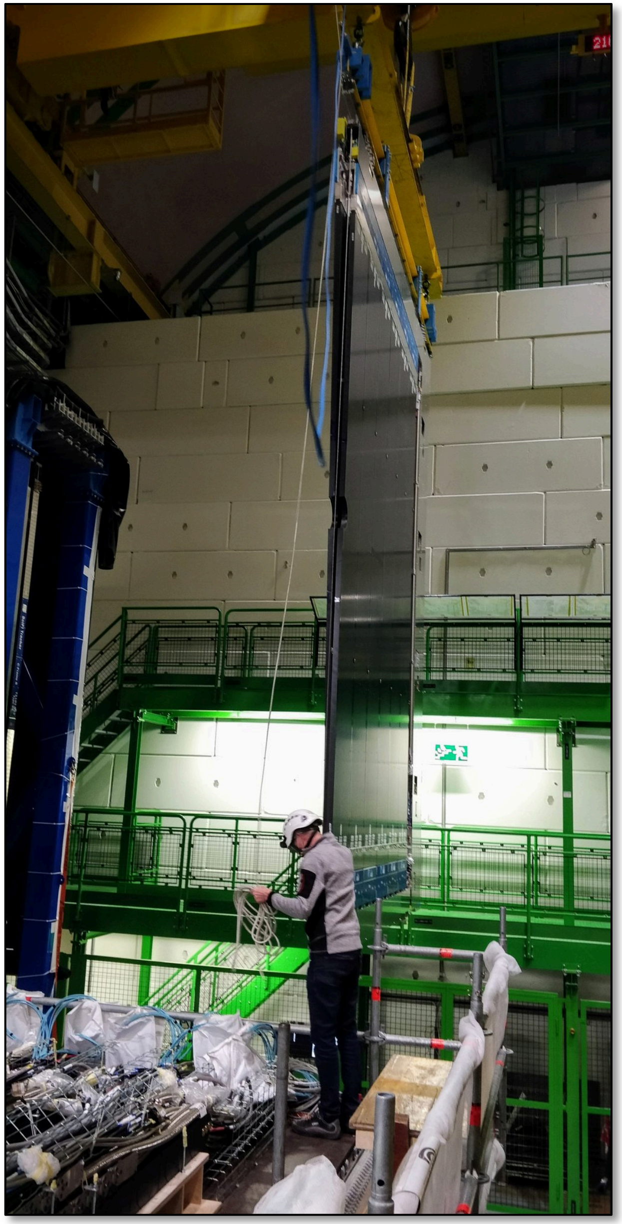
LHC schedule:
https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm

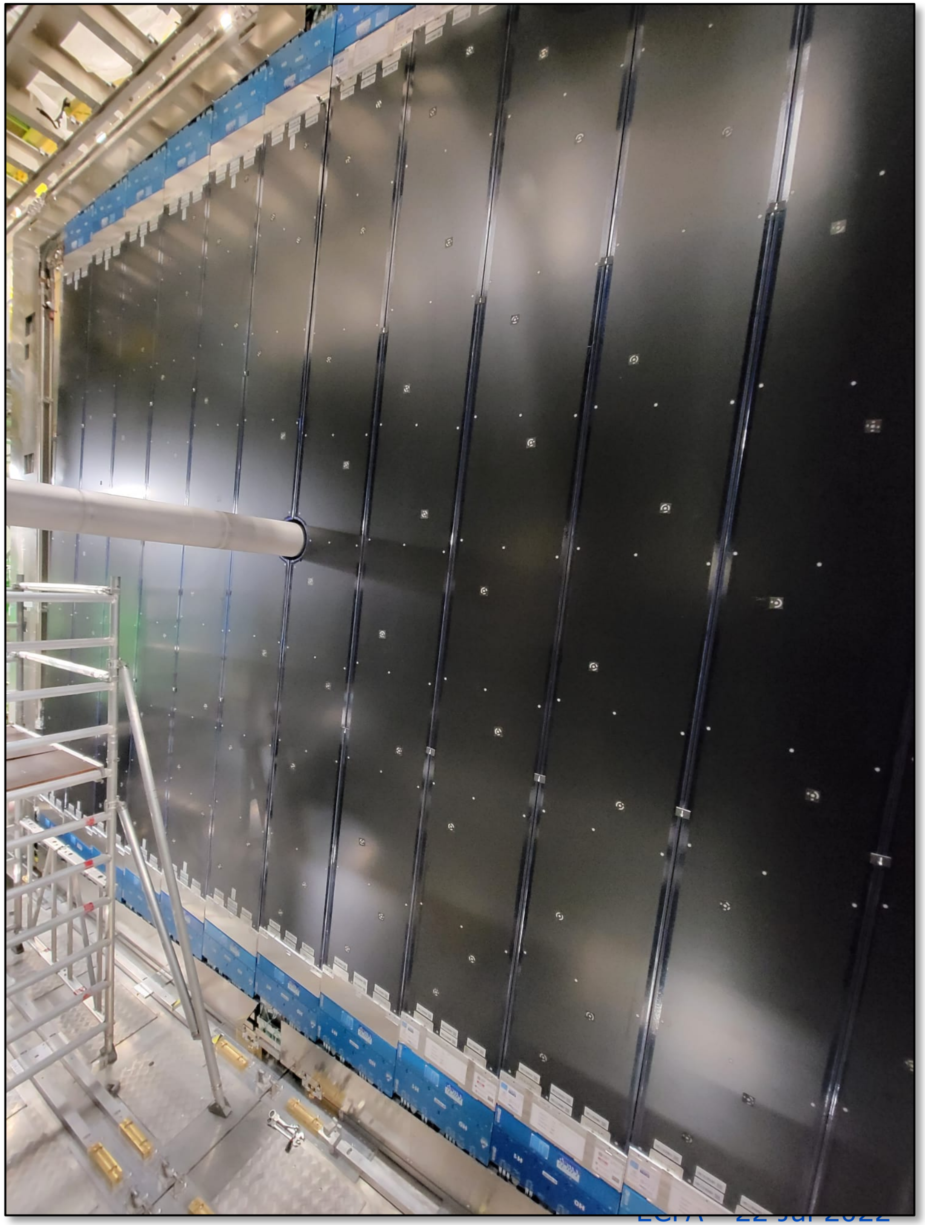
LHCb: VELO



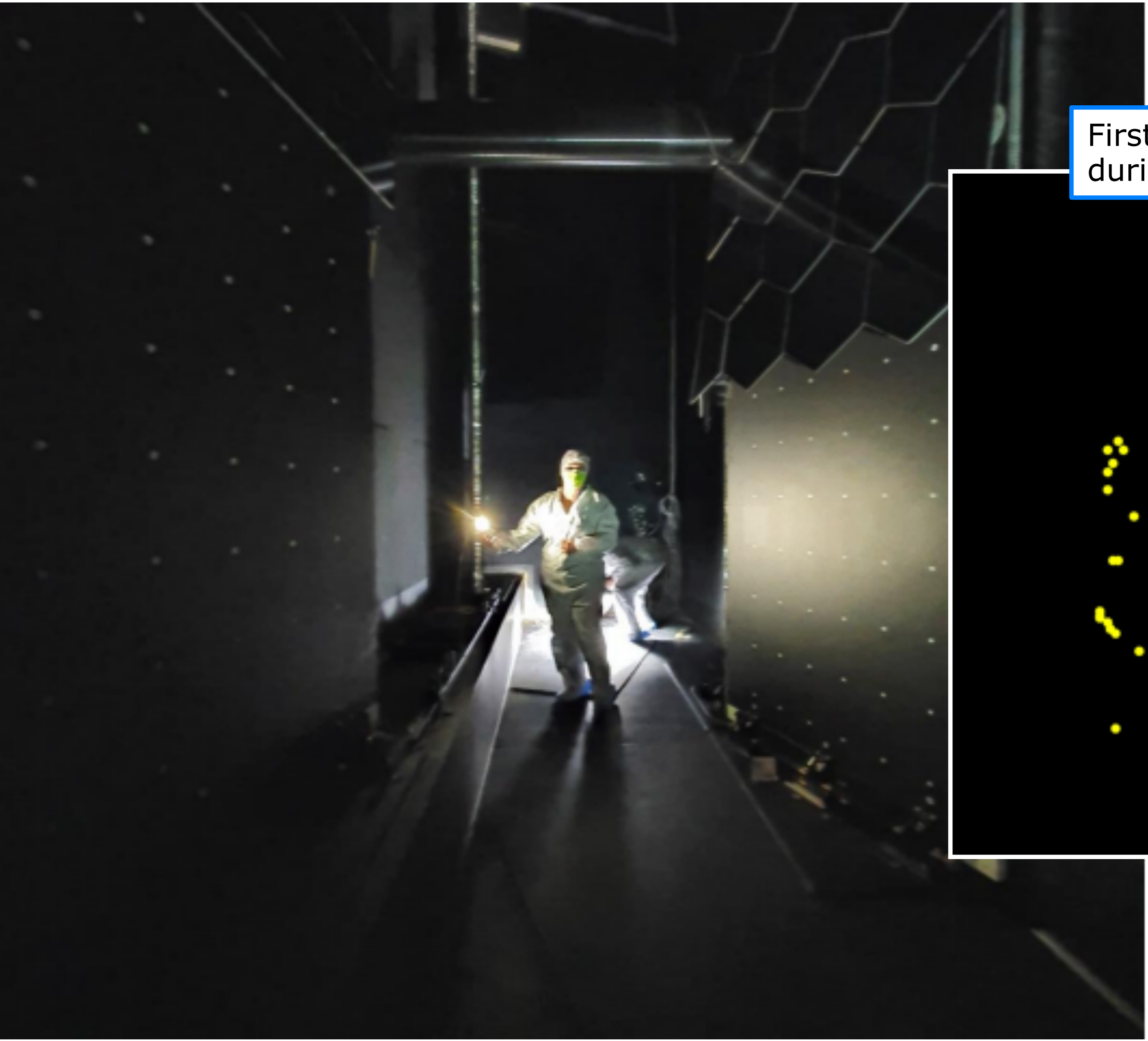


LHCb: Tracker

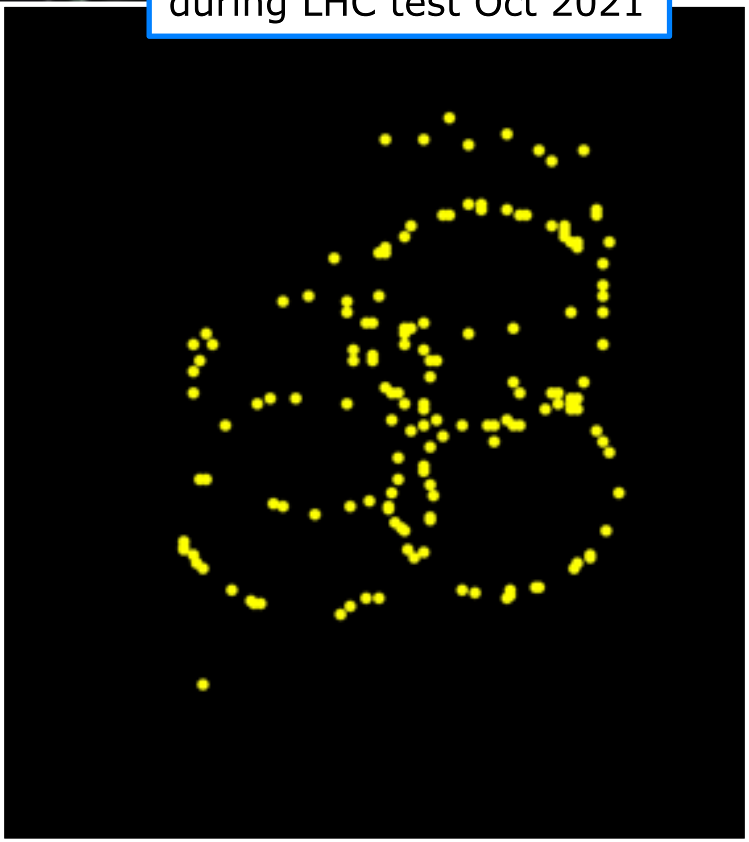




LHCb: Ring Imaging Cherenkov

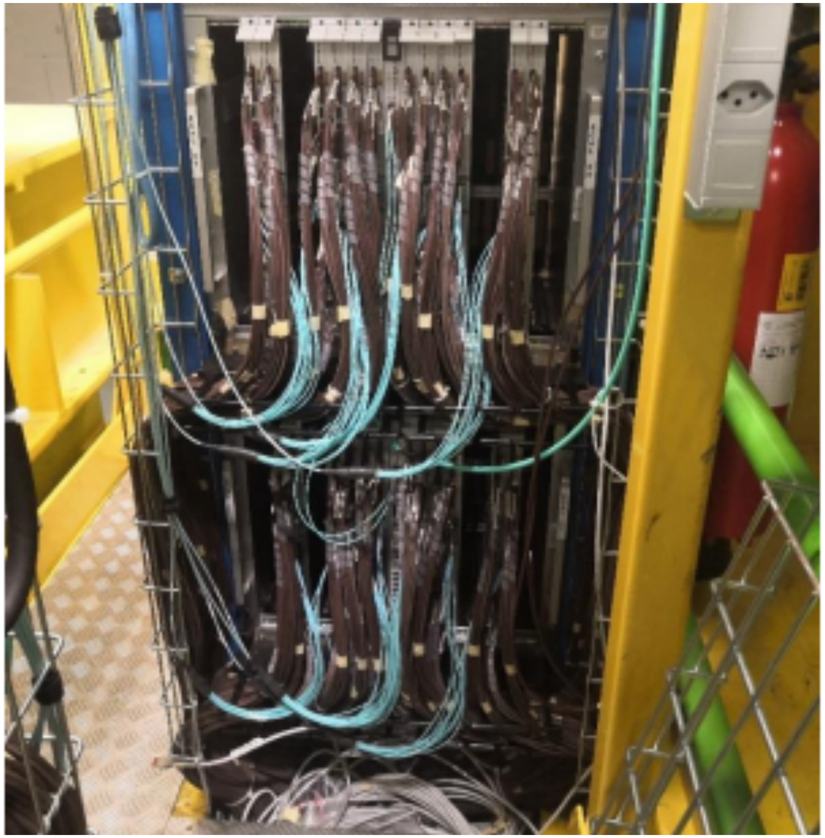


First rings in RICH2 during LHC test Oct 2021

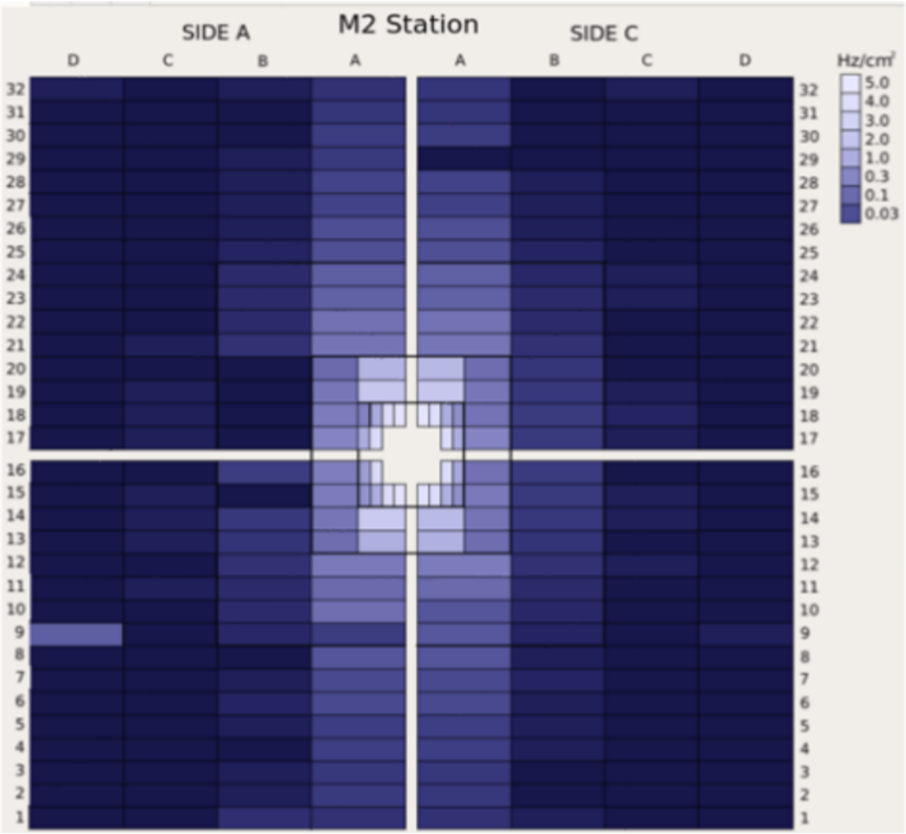


LHCb: Calorimeter & Muon detector

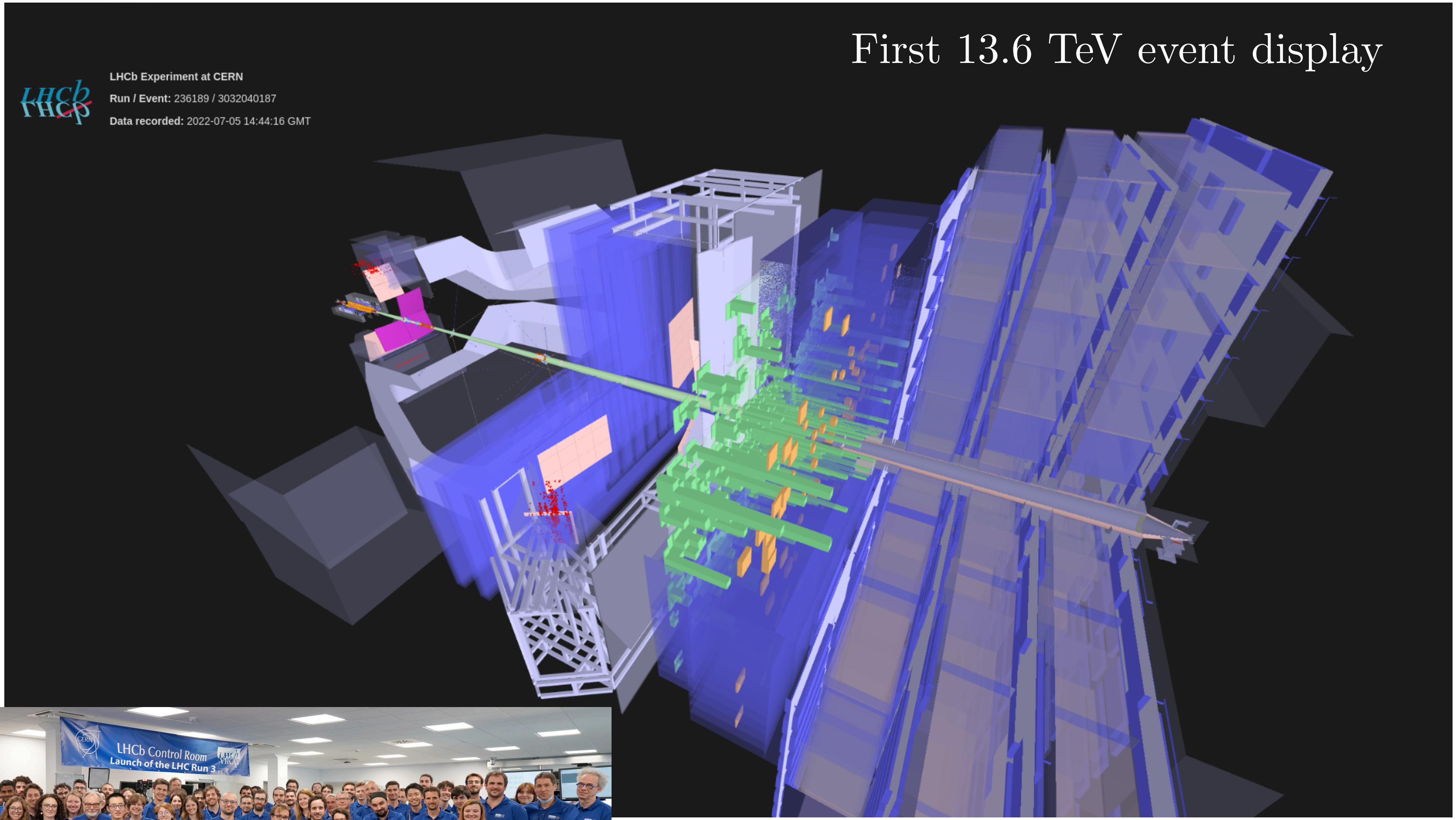
New CALO frontend and control boards



MUON Station 2 Hit map during machine test Oct 2021



First data at 13.6 TeV

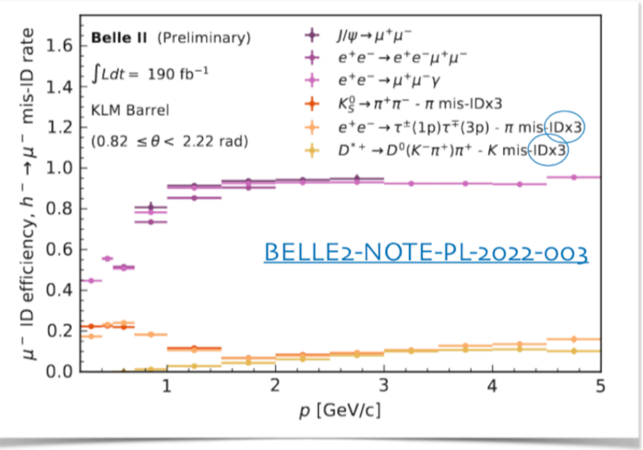


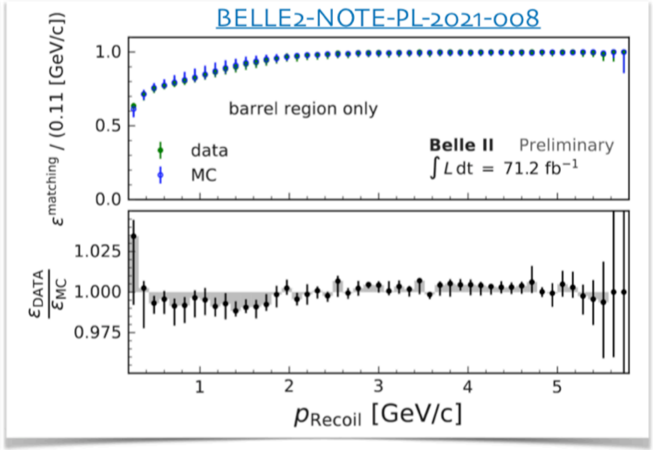
Belle II: good detector performance

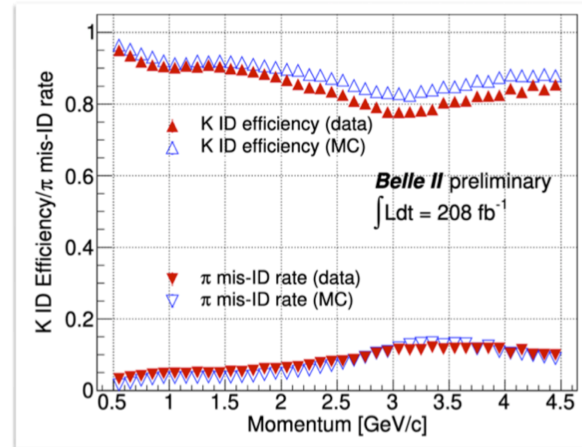
Good Lepton ID, Muon/ Electron-ID over/under performing wrt Belle, improvements in progress

High photon detection efficiency, Belle-like resolution π^0 mass

Good kaon identification, underperforming wrt Belle, improvements in progress

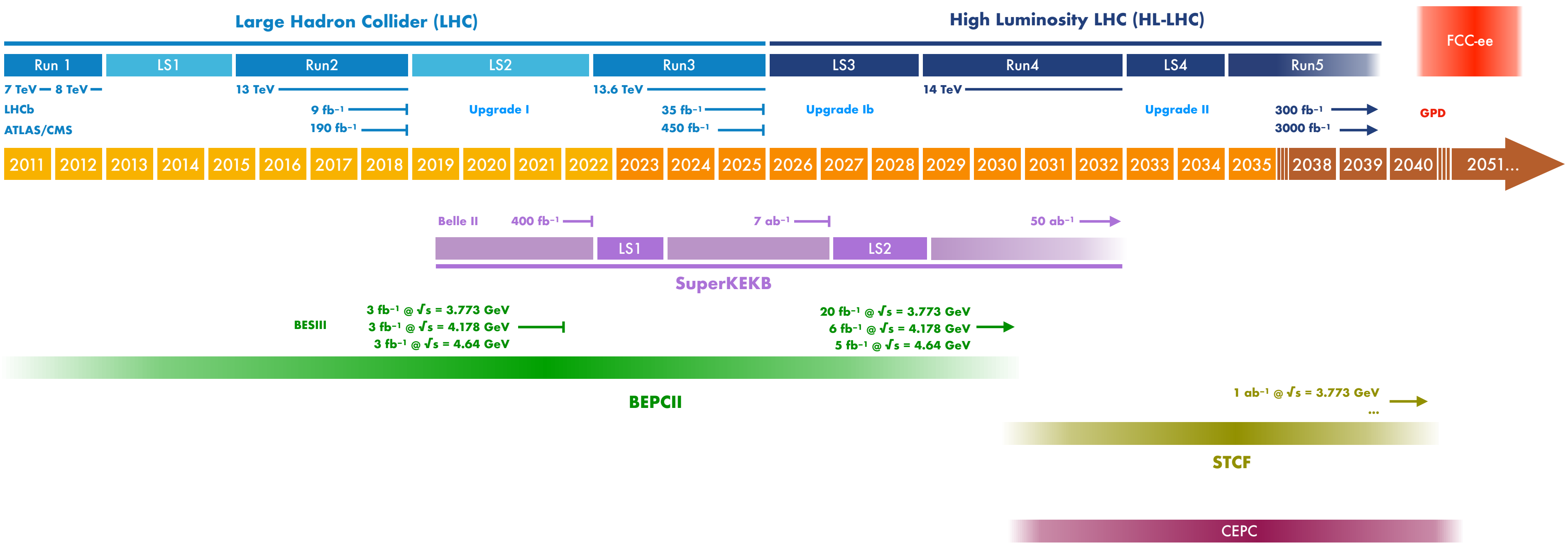






E. Manoni, Moriond, 17 Mar 2022

Future Plans

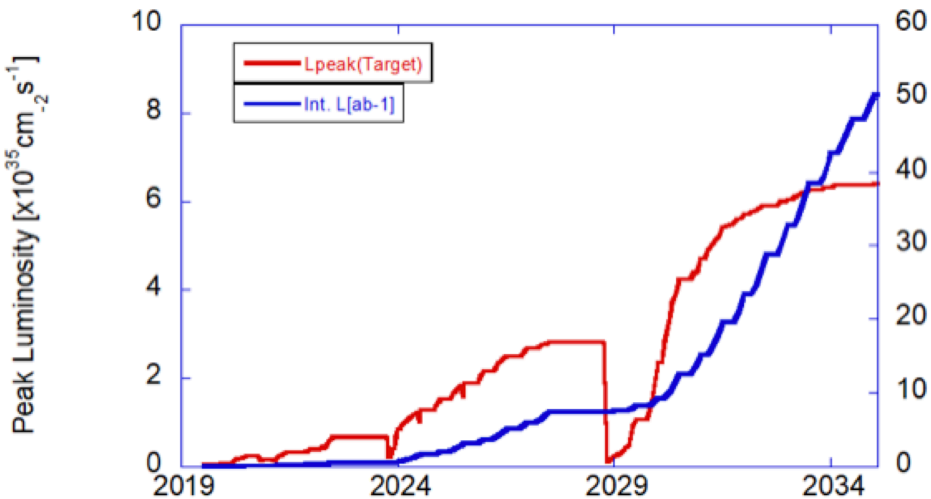


Archilli, Altmannshofer, arXiv:2206.11331

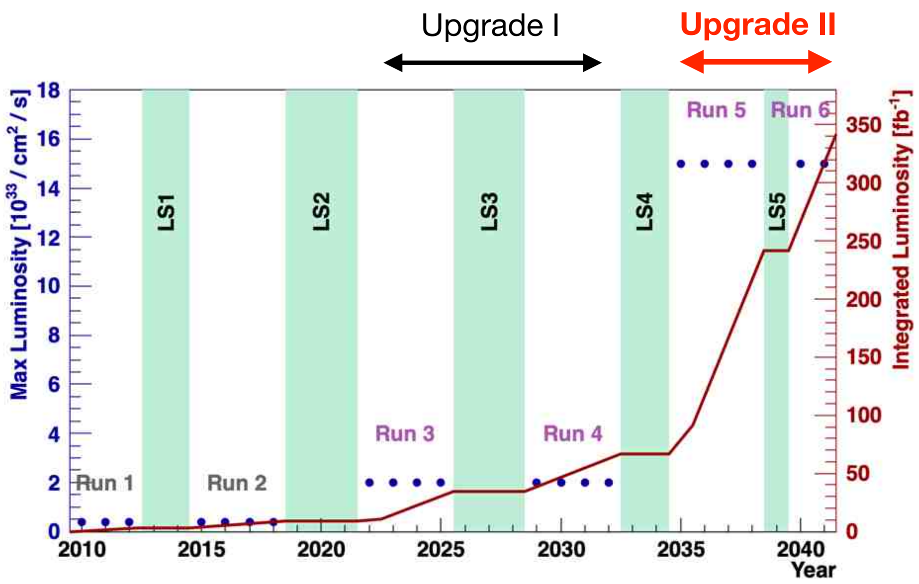
Luminosity prospects for Belle II and LHCb

- 2027:
  - Belle II: ~7 ab^{-1}
  - LHCb: ~30 fb^{-1}
- 2035:
  - Belle II: ~50 ab^{-1}
  - LHCb: ~60 fb^{-1}

} Similar sensitivity



SuperKEKB plan, updated June 2022



From M.Palutan, LHCP2022

Upgrades

arXiv:2203.11349

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Snowmass Whitepaper:
The Belle II Detector Upgrade Program

Belle II Collaboration

March 23, 2022

Abstract

We describe the planned near-term and potential longer-term upgrades of the Belle II detector at the SuperKEKB electron-positron collider in Tsukuba, Japan. These upgrades will allow increasingly sensitive searches for possible new physics beyond the Standard Model in flavor, tau, electroweak and dark sector physics that are both complementary to and competitive with the LHC and other experiments. We encourage the instrumentation-frontier community to contribute and study upgrade ideas as part of the Snowmass process.

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LHCb-TDR-023

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-LHCC-2021-012
LHCb TDR 23
24 February 2022

Framework TDR for the LHCb Upgrade II

Opportunities in flavour physics, and beyond, in the HL-LHC era

The LHCb collaboration

Abstract

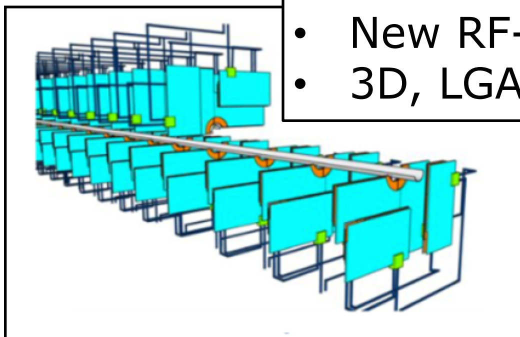
This document is the Framework Technical Design Report for the Upgrade II of the LHCb experiment, which is proposed for the long shutdown 4 of the LHC. The upgraded detector will operate at a maximum luminosity of $1.5 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$, with the aim of integrating $\sim 300\,\mathrm{fb^{-1}}$ through the lifetime of the high-luminosity LHC (HL-LHC). The collected data will allow to fully exploit the flavour-physics opportunities of the HL-LHC, probing a wide range of physics observables with unprecedented accuracy. In particular, the new physics mass scale probed, for fixed couplings, will almost double as compared with the pre-HL-LHC era.

The accomplishment of this ambitious programme will require that the current detector performance is maintained at the maximum expected pile-up of $\sim$40, and even improved in certain specific domains. To meet this challenge, it is foreseen to replace all of the existing spectrometer components to increase the granularity, reduce the amount of material in the detector and to exploit the use of new technologies including precision timing of the order of a few tens of picoseconds. The design options for each sub-detector are discussed, and the ongoing efforts to face the associated technology challenges. For the first time, elements of the environmental impact of the project are considered. Finally, details are given about the project schedule, the cost envelope and the participating institutes.

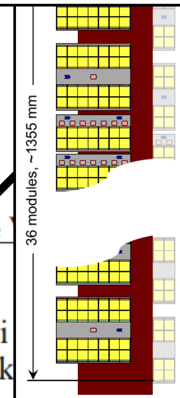
Approved by LHCC, 2022

Planning for Upgrade II: Tracking

VELO pixel
- Add Timing
- New RF-foil
- 3D, LGADs, 28nm

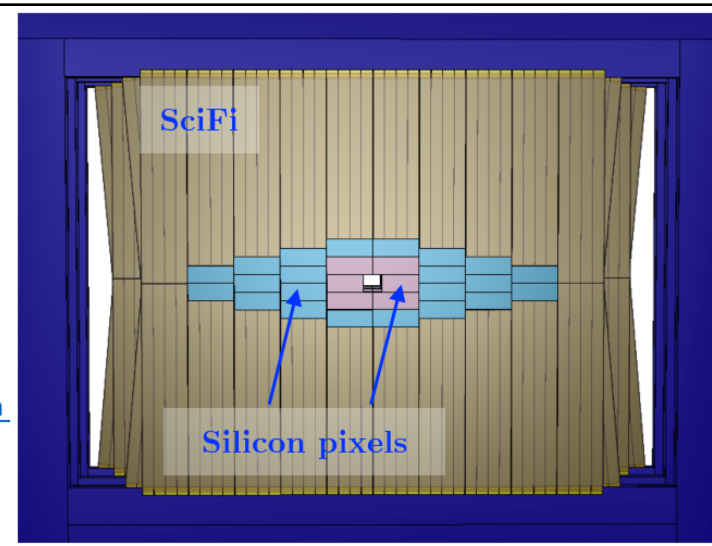


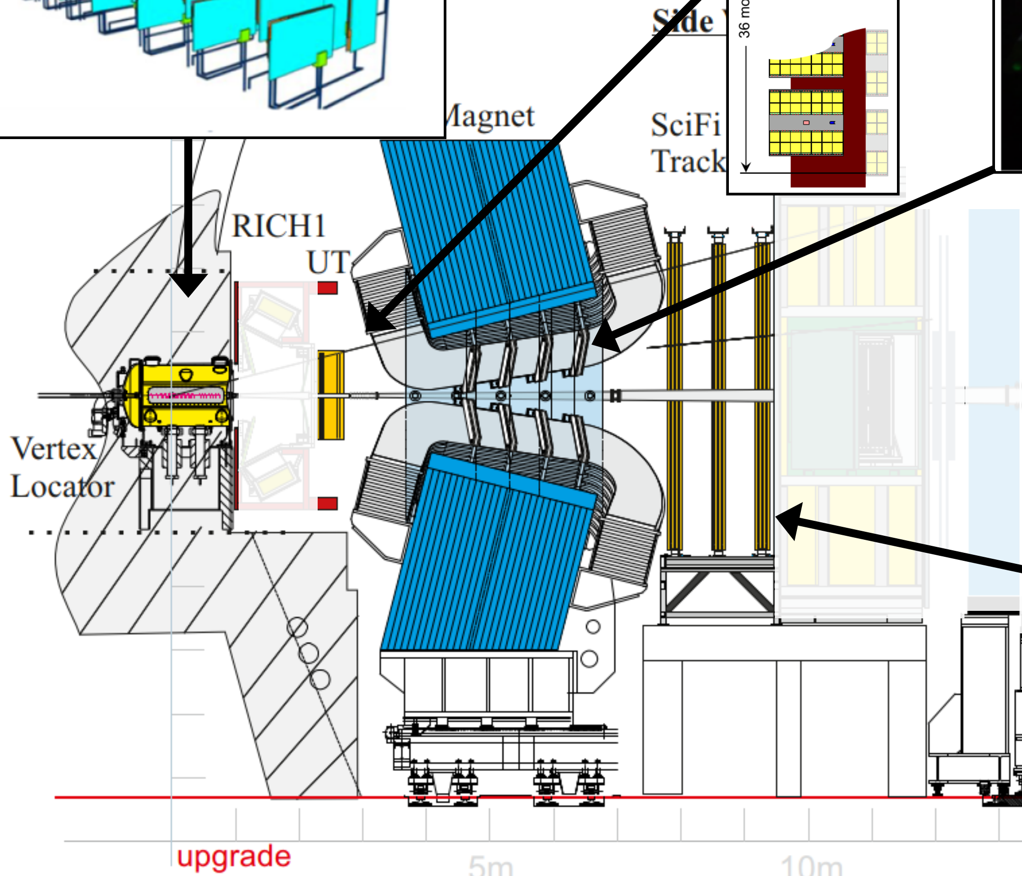
UT pixel
- MAPS, radiation tolerant



Magnet Station new

Mighty Tracker
- MAPS pixel and Scintillating fibers





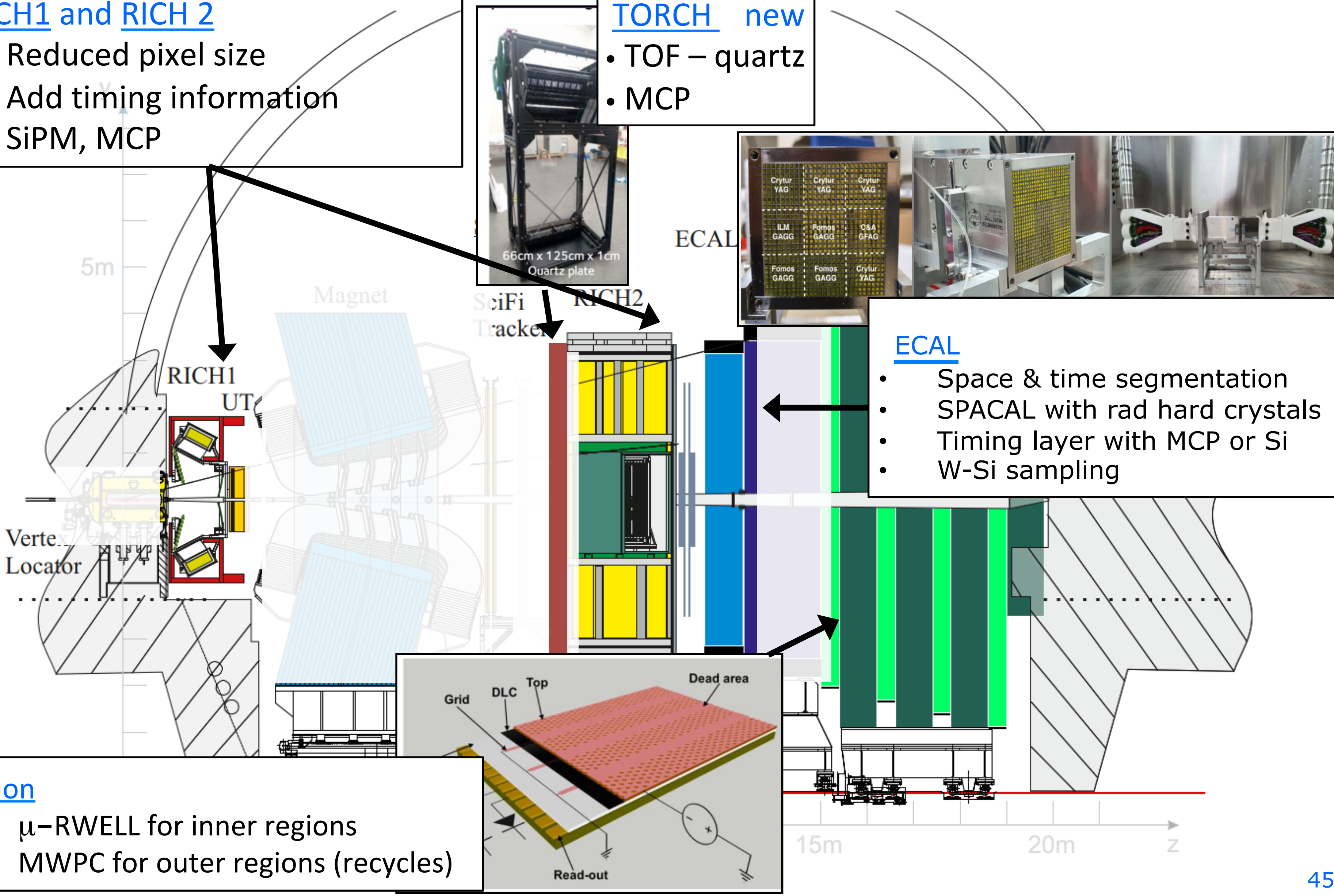
Planning for Upgrade II: PID detectors

RICH1 and RICH 2
- Reduced pixel size
- Add timing information
- SiPM, MCP

TORCH new
- TOF – quartz
- MCP

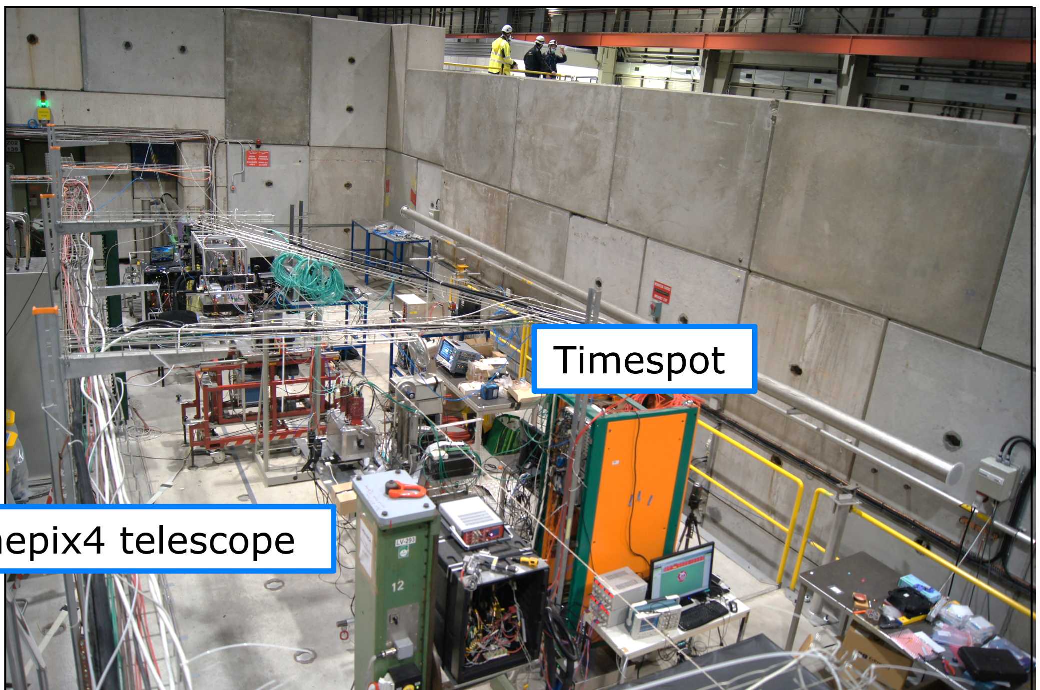
ECAL
- Space & time segmentation
- SPACAL with rad hard crystals
- Timing layer with MCP or Si
- W-Si sampling

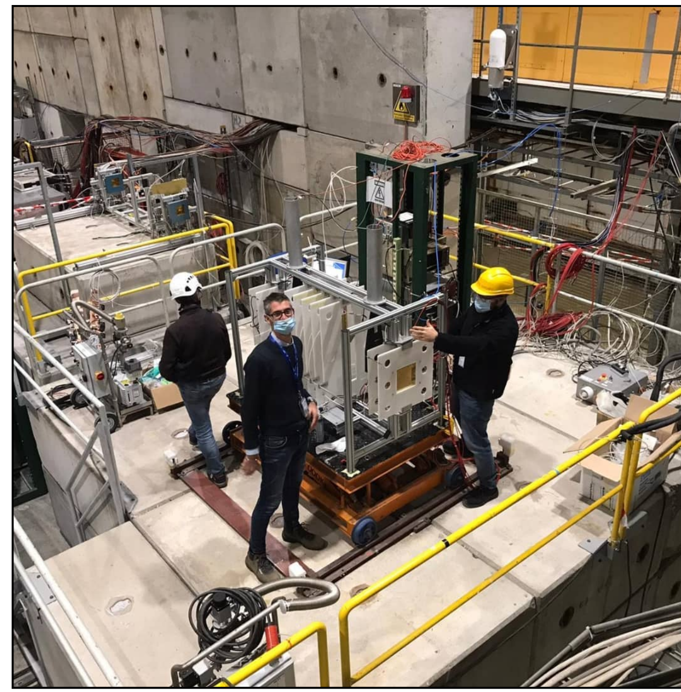
Muon
- μ–RWELL for inner regions
- MWPC for outer regions (recycles)



Planning for Upgrade II: Testbeam

- Activities for RICH, VELO, ECAL, MUON
- Lots of opportunities for R&D in coming decade!





Prospects

arXiv:2207.06307

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

arXiv:2207.06307v1 [hep-ex] 13 Jul 2022

Snowmass White Paper: Belle II physics reach and plans for the next decade and beyond

Belle II Collaboration

Abstract

We describe the physics potential of the Belle II experiment with electron-positron data corresponding to integrated luminosities of $1\,\mathrm{ab}^{-1}$ to $50\,\mathrm{ab}^{-1}$. We discuss Belle II's unique capabilities in reconstructing neutral particles, neutrinos and other "invisible" particles, and inclusive final states to probe non-standard-model physics. We project sensitivities for compelling measurements that are of primary relevance and where Belle II reach is unique or world leading.

arXiv:1808.08865

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-LHCC-2018-027
LHCB-PUB-2018-009
27 August 2018

arXiv:1808.08865v4 [hep-ex] 5 Apr 2019

Physics case for an LHCb Upgrade II

Opportunities in flavour physics, and beyond, in the HL-LHC era

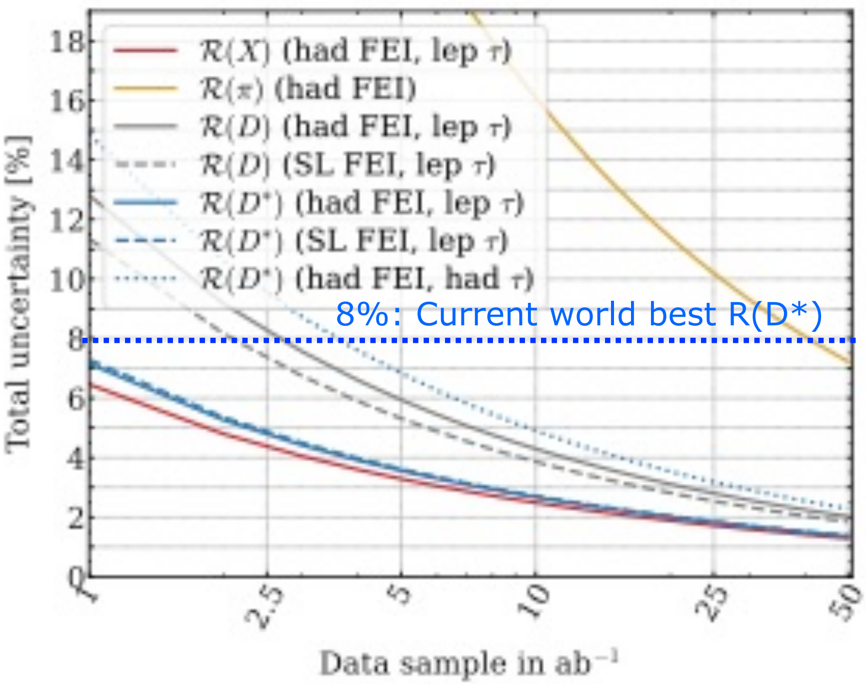
The LHCb collaboration

Abstract

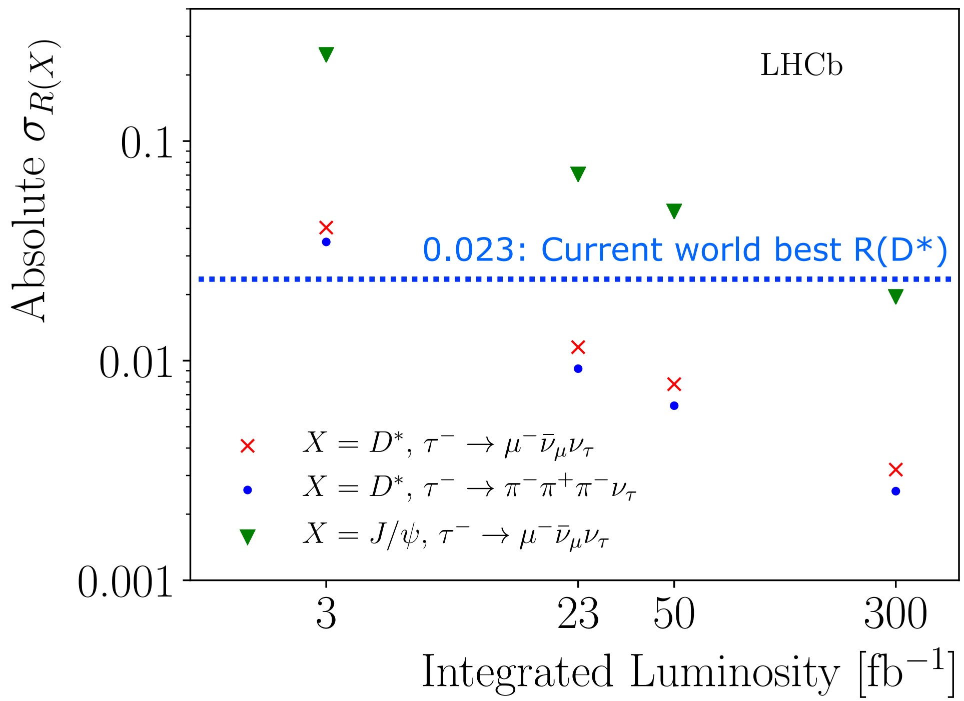
The LHCb Upgrade II will fully exploit the flavour-physics opportunities of the HL-LHC, and study additional physics topics that take advantage of the forward acceptance of the LHCb spectrometer. The LHCb Upgrade I will begin operation in 2020. Consolidation will occur, and modest enhancements of the Upgrade I detector will be installed, in Long Shutdown 3 of the LHC (2025) and these are discussed here. The main Upgrade II detector will be installed in long shutdown 4 of the LHC (2030) and will build on the strengths of the current LHCb experiment and the Upgrade I. It will operate at a luminosity up to $2\times10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, ten times that of the Upgrade I detector. New detector components will improve the intrinsic performance of the experiment in certain key areas. An Expression Of Interest proposing Upgrade II was submitted in February 2017. The physics case for the Upgrade II is presented here in more depth. *CP*-violating phases will be measured with precisions unattainable at any other envisaged facility. The experiment will probe $b\to s\ell^+\ell^-$ and $b\to d\ell^+\ell^-$ transitions in both muon and electron decays in modes not accessible at Upgrade I. Minimal flavour violation will be tested with a precision measurement of the ratio of $\mathcal{B}(B^0\to\mu^+\mu^-)/\mathcal{B}(B^0_s\to\mu^+\mu^-)$. Probing charm *CP* violation at the 10^{-5} level may result in its long sought discovery. Major advances in hadron spectroscopy will be possible, which will be powerful probes of low energy QCD. Upgrade II potentially will have the highest sensitivity of all the LHC experiments on the Higgs to charm-quark couplings. Generically, the new physics mass scale probed, for fixed couplings, will almost double compared with the pre-HL-LHC era; this extended reach for flavour physics is similar to that which would be achieved by the HE-LHC proposal for the energy frontier.

R(D$^{(*)}$) sensitivity

Belle II



LHCb



b→sll complementarity!

- Belle II prospects:

$B \to K\nu\nu$

Uncertainty on relative signal strength μ

Decay	1 ab^{-1}	5 ab^{-1}	10 ab^{-1}	50 ab^{-1}
$B^+ \to K^+\nu\bar{\nu}$	0.55 (0.37)	0.28 (0.19)	0.21 (0.14)	0.11 (0.08)
$B^0 \to K^0_S\nu\bar{\nu}$	2.06 (1.37)	1.31 (0.87)	1.05 (0.70)	0.59 (0.40)
$B^+ \to K^{*+}\nu\bar{\nu}$	2.04 (1.45)	1.06 (0.75)	0.83 (0.59)	0.53 (0.38)
$B^0 \to K^{*0}\nu\bar{\nu}$	1.08 (0.72)	0.60 (0.40)	0.49 (0.33)	0.34 (0.23)

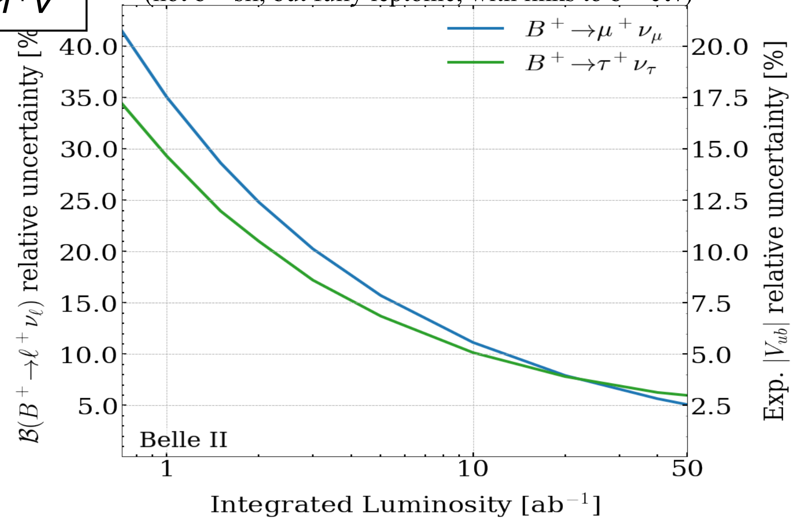
$B^0 \to K^{*0}\tau\tau$

$\mathcal{B}(B^0 \to K^{*0}\tau\tau)$ (had tag)

ab^{-1}	"Baseline" scenario	"Improved" scenario
1	$< 3.2 \times 10^{-3}$	$< 1.2 \times 10^{-3}$
5	$< 2.0 \times 10^{-3}$	$< 6.8 \times 10^{-4}$
10	$< 1.8 \times 10^{-3}$	$< 6.5 \times 10^{-4}$
50	$< 1.6 \times 10^{-3}$	$< 5.3 \times 10^{-4}$

$B^+ \to l^+\nu$

(not b→sll, but fully leptonic, with links to b→cτν)



- LHCb prospects:

$B \to Kee$

ield	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$B^+ \to K^+e^+e^-$	1 120	3 300	7 500	46 000
$B^0 \to K^{*0}e^+e^-$	490	1 400	3 300	20 000
$B^0_s \to \phi e^+e^-$	80	230	530	3 300
$\Lambda^0_b \to pKe^+e^-$	120	360	820	5 000
$B^+ \to \pi^+e^+e^-$	20	70	150	900

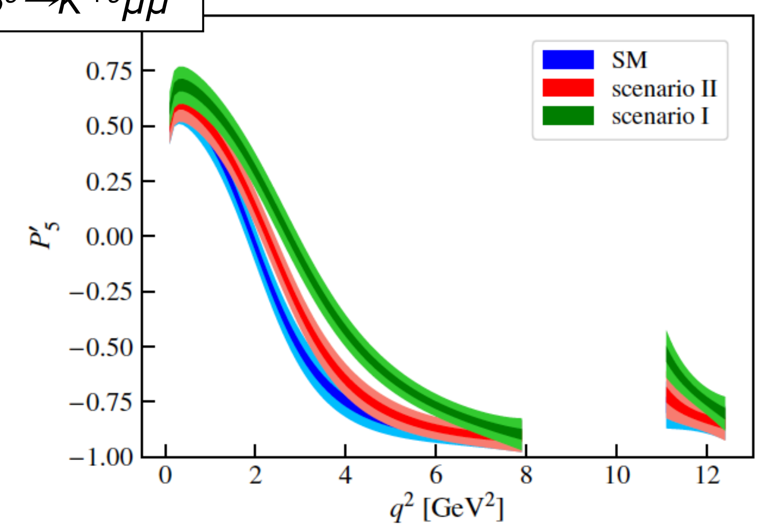
$B^0_s \to \mu\mu$

(assuming 4% syst uncertainty)

23 fb^{-1}	300 fb^{-1}
0.30 x 10^{-9}	0.16 x 10^{-9}

$B^0 \to K^{*0}\mu\mu$

P_5' after Run-3 (23 fb^{-1})



Prospects

Observable	2022 Belle(II), BaBar	Belle-II 5 ab^{-1}	Belle-II 50 ab^{-1}	Belle-II 250 ab^{-1}
$S_{CP}(B \to K^{*0}\gamma)$	0.32	0.11	0.035	0.015
$R(B \to K^{*}\ell^{+}\ell^{-})^{\dagger}$	0.26	0.09	0.03	0.01
$R(B \to D^{*}\tau\nu)$	0.018	0.009	0.0045	<0.003
$R(B \to D\tau\nu)$	0.034	0.016	0.008	<0.003
$\mathcal{B}(B \to \tau\nu)$	24%	9%	4%	2%
$B(B \to K^{*}\nu\bar{\nu})$	–	25%	9%	4%
$\mathcal{B}(\tau \to \mu\gamma)$ UL	42×10^{-9}	22×10^{-9}	6.9×10^{-9}	3.1×10^{-9}
$\mathcal{B}(\tau \to \mu\mu\mu)$ UL	21×10^{-9}	3.6×10^{-9}	0.36×10^{-9}	0.073×10^{-9}

Belle II, arXiv:2203.11349

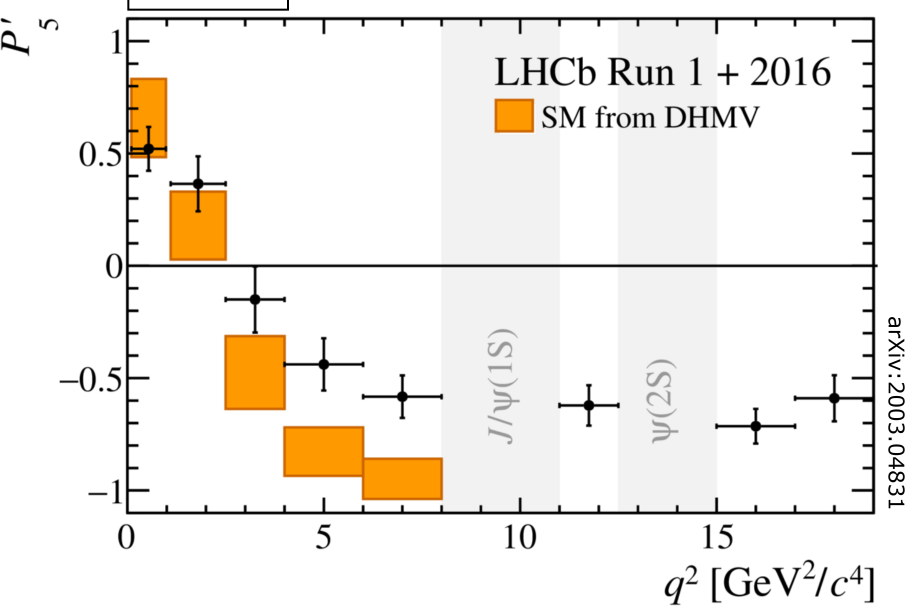
Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
Rare Decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	69%	[40, 41]	41%	27%	11%
$S_{\mu\mu}\ (B^0_s \to \mu^+\mu^-)$	—		—	—	0.2
$A^{(2)}_{\mathrm{T}}\ (B^0 \to K^{*0}e^+e^-)$	0.10	[52]	0.060	0.043	0.016
$A^{\mathrm{Im}}_{\mathrm{T}}\ (B^0 \to K^{*0}e^+e^-)$	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}^{\Delta\Gamma}_{\phi\gamma}(B^0_s \to \phi\gamma)$	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}(B^0_s \to \phi\gamma)$	0.32	[51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda^0_b \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[53]	0.148	0.097	0.038
Lepton Universality Tests					
$R_K\ (B^+ \to K^+\ell^+\ell^-)$	0.044	[12]	0.025	0.017	0.007
$R_{K^*}\ (B^0 \to K^{*0}\ell^+\ell^-)$	0.12	[61]	0.034	0.022	0.009
$R(D^*)\ (B^0 \to D^{*-}\ell^+\nu_\ell)$	0.026	[62, 64]	0.007	0.005	0.002

LHCb, Framework TDR, LHCb-TDR-023

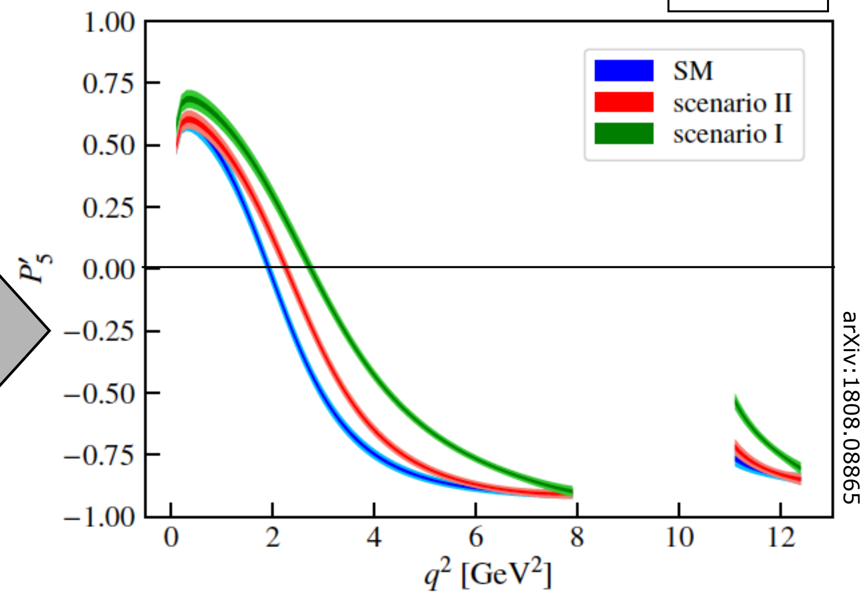
Summary

- Precision measurements to scrutinize the Standard Model
- Precision measurements reach very high mass scales
- Precision measurements are statistically limited
- Belle II and LHCb complementary and strengthen each other
- Lots of opportunities to contribute to R&D

2020



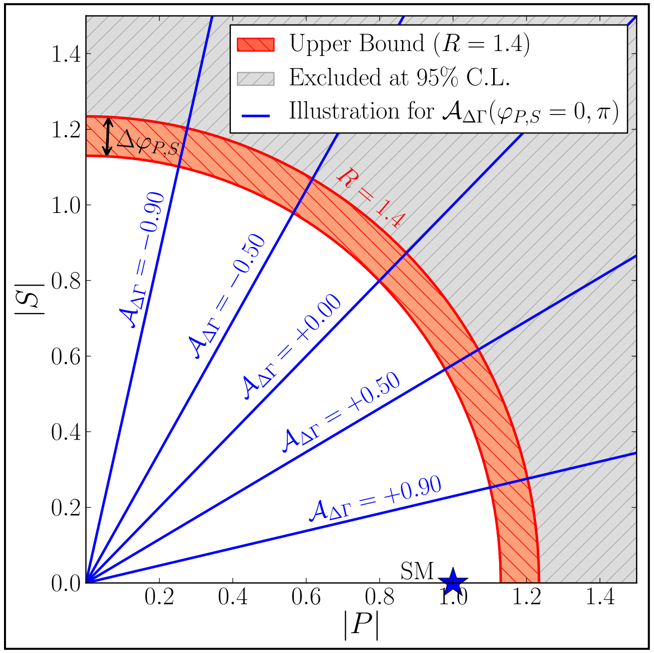
2040



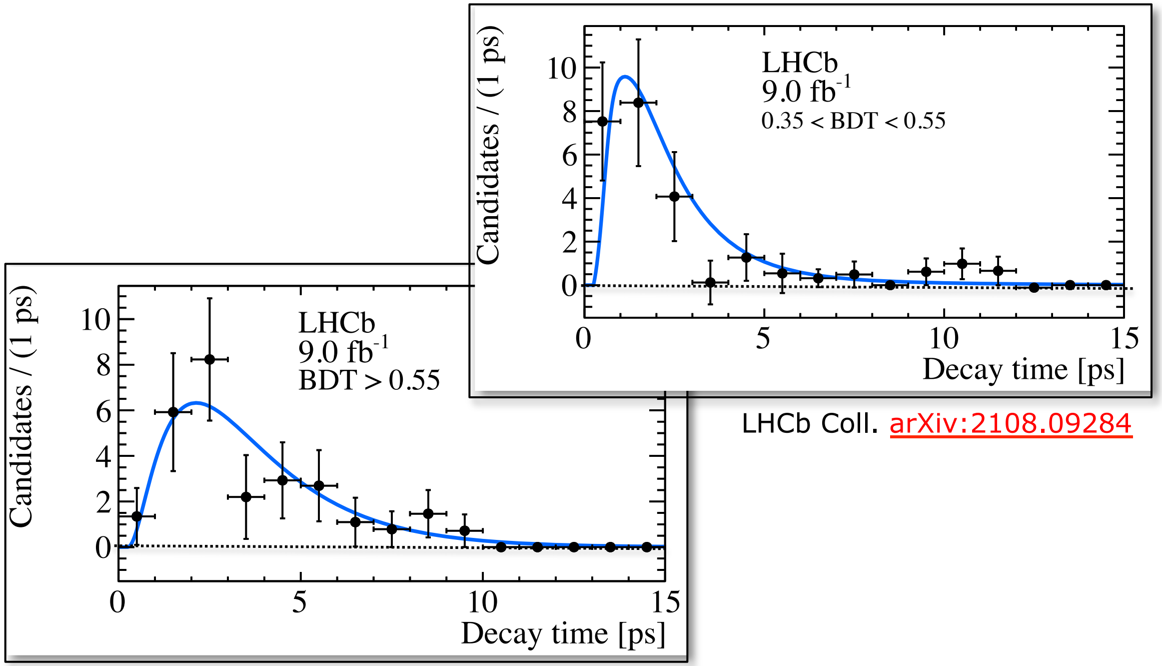
Backups

$B_s^0 \to \mu^+\mu^-$ (LHCb)

- More observables accessible
- New Physics can lead to different CP structure of final state
  - Affects the mix of long and short-living B_s^0 mesons



De Bruyn, Fleischer, NT, et al., PRL109 (2012) 041801



LHCb Coll. arXiv:2108.09284

$$\tau(B_s^0 \to \mu^+\mu^-) = 2.07 \pm 0.29 \pm 0.03\,\mathrm{ps}$$

Historical record of indirect discoveries

GIM mechanism in $K^0 \to \mu\mu$

Weak Interactions with Lepton-Hadron Symmetry*

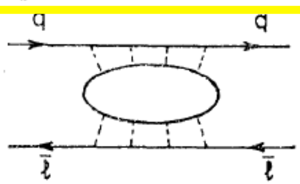
S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Mills theory is discussed.

splitting, beginning at order $G(G\Lambda^2)$, as well as contributions to such unobserved decay modes as $K_2 \to \mu^+ + \mu^-$, $K^+ \to \pi^+ + l + \bar{l}$, etc., involving neutral lepton

We wish to propose a simple model in which the divergences are properly ordered. Our model is founded in a quark model, but one involving four, not three, fundamental fermions; the weak interactions are medi-

new quantum number $\mathcal{C}$ for charm.



Glashow, Iliopoulos, Maiani,
Phys.Rev. D2 (1970) 1285

CP violation, $K_L^0 \to \pi\pi$

27 July 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the 2π decay of the K_2^0 meson. Several previous experiments have

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

***CP*-Violation in the Renormalizable Theory of Weak Interaction**

Makoto Kobayashi and Toshihide Maskawa
Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

doublet with the same charge assignment. This is because all phases of elements of a 3×3 unitary matrix cannot be absorbed into the phase convention of six fields. This possibility of *CP*-violation will be discussed later on.

Christenson, Cronin, Fitch, Turlay,
Phys.Rev.Lett. 13 (1964) 138
Kobayashi, Maskawa,
Prog.Theor. Phys. 49 (1973) 652

$B^0 \leftrightarrow \overline{B}^0$ mixing

DESY 87-029
April 1987

OBSERVATION OF B^0-$\overline{B}^0$ MIXING

The ARGUS Collaboration

In summary, the combined evidence of the investigation of B^0 meson pairs, lepton pairs and B^0 meson-lepton events on the $\Upsilon(4S)$ leads to the conclusion that B^0-$\overline{B}^0$ mixing has been observed and is substantial.

Parameters	Comments
$r > 0.09$ 90% CL	This experiment
$x > 0.44$	This experiment
$B^{\frac{1}{2}} f_B \approx f_\pi < 160$ MeV	B meson (≈ pion) decay constant
$m_b < 5\mathrm{GeV}/c^2$	b-quark mass
$\tau_b < 1.4 \cdot 10^{-12}$s	B meson lifetime
$\lvert V_{td} \rvert < 0.018$	Kobayashi-Maskawa matrix element
$\eta_{QCD} < 0.86$	QCD correction factor [17]
$m_t > 50\mathrm{GeV}/c^2$	t quark mass

ARGUS Coll.
Phys.Lett.B192 (1987) 245

"Discovery" of charm

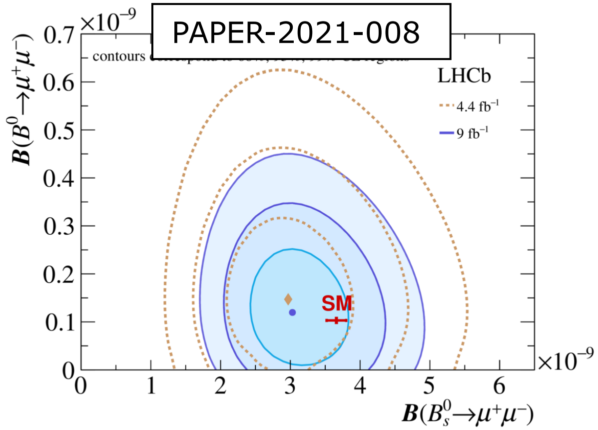
"Discovery" of beauty

"Discovery" of top

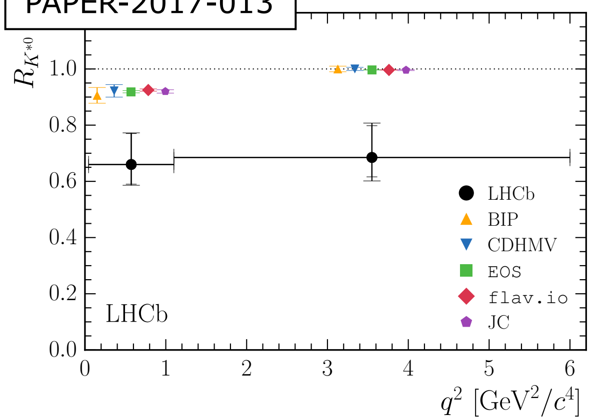
Anomalies

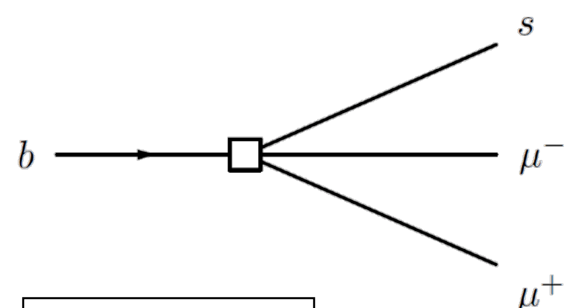
- What is the overall picture? Combination statistically not simple

PAPER-2021-008

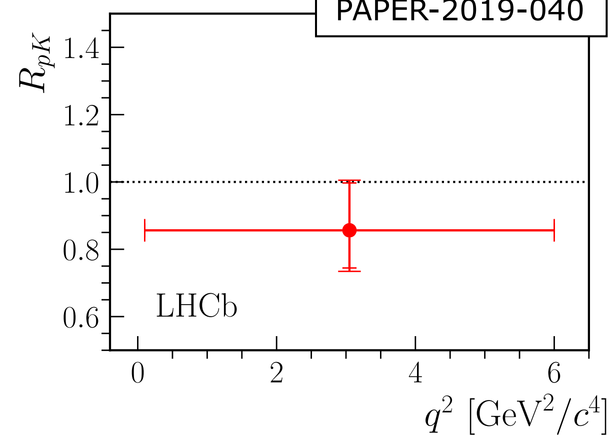


PAPER-2017-013



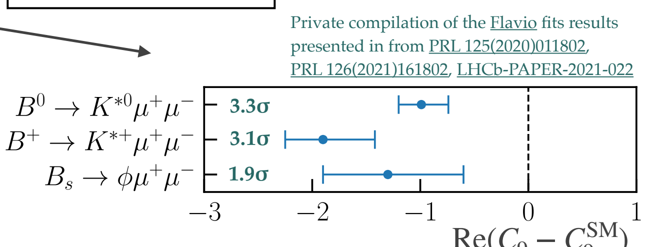


PAPER-2019-040

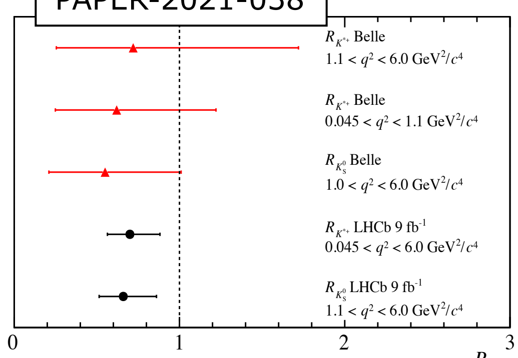


+ Angular Fits?

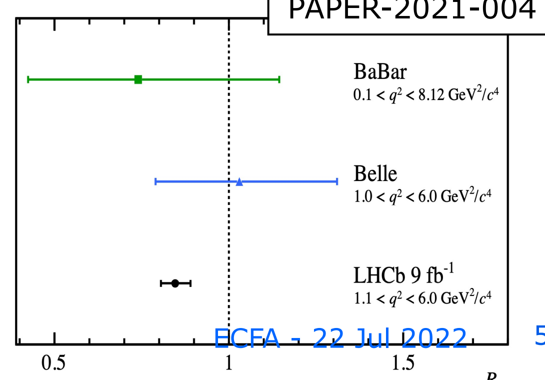
Private compilation of the Flavio fits results presented in from PRL 125(2020)011802, PRL 126(2021)161802, LHCb-PAPER-2021-022



PAPER-2021-038



PAPER-2021-004



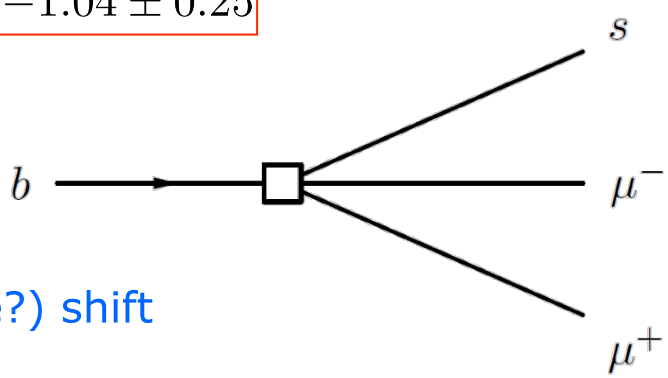
From: Martino Borsato, Flavour Anomaly Workshop, 20 Oct 2021, https://indico.cern.ch/event/1055780/

Effective couplings

Model independent fits:

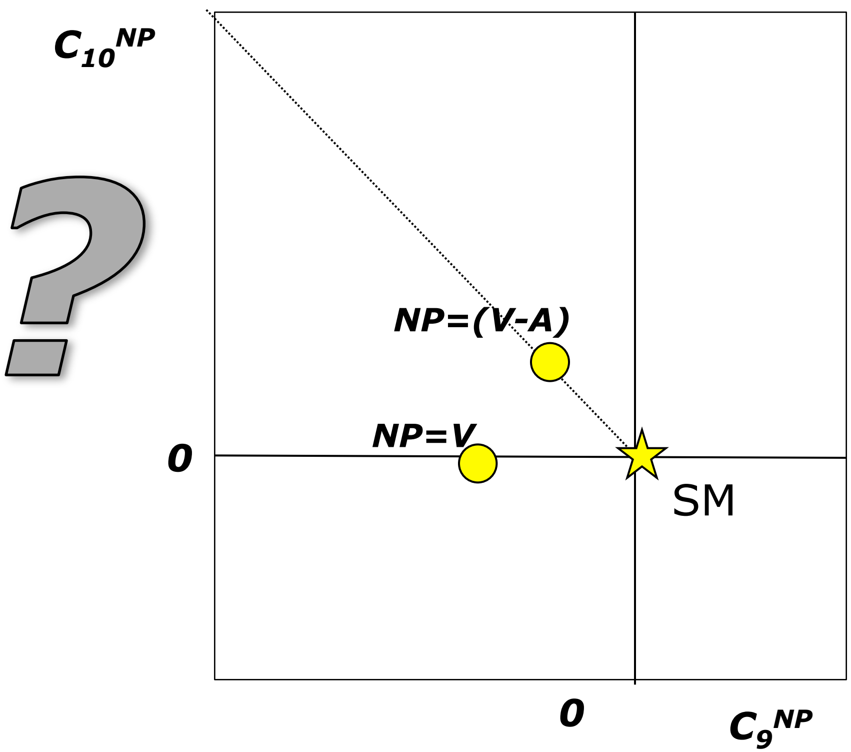
LHCb, JHEP 02 (2016) 104

$$\Delta \mathrm{Re}(\mathcal{C}_9) = -1.04 \pm 0.25$$

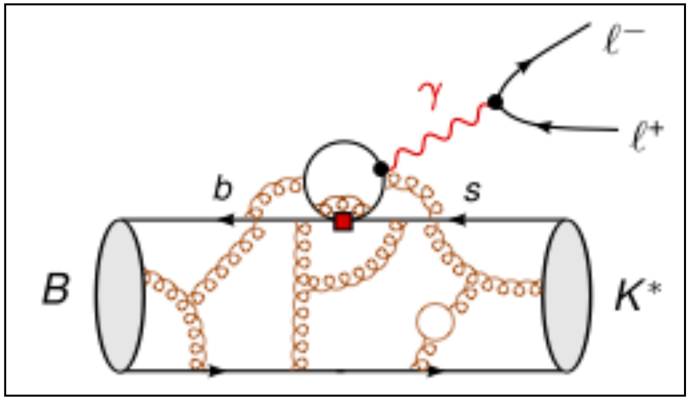


- C_9^{NP} deviates from 0 by >4σ
- Independent fits by many groups favour:
  - C_9^{NP}=-1 or
  - C_9^{NP}=-C_{10}^{NP}

➢ *All* measurements (175) agree with a single (simple?) shift

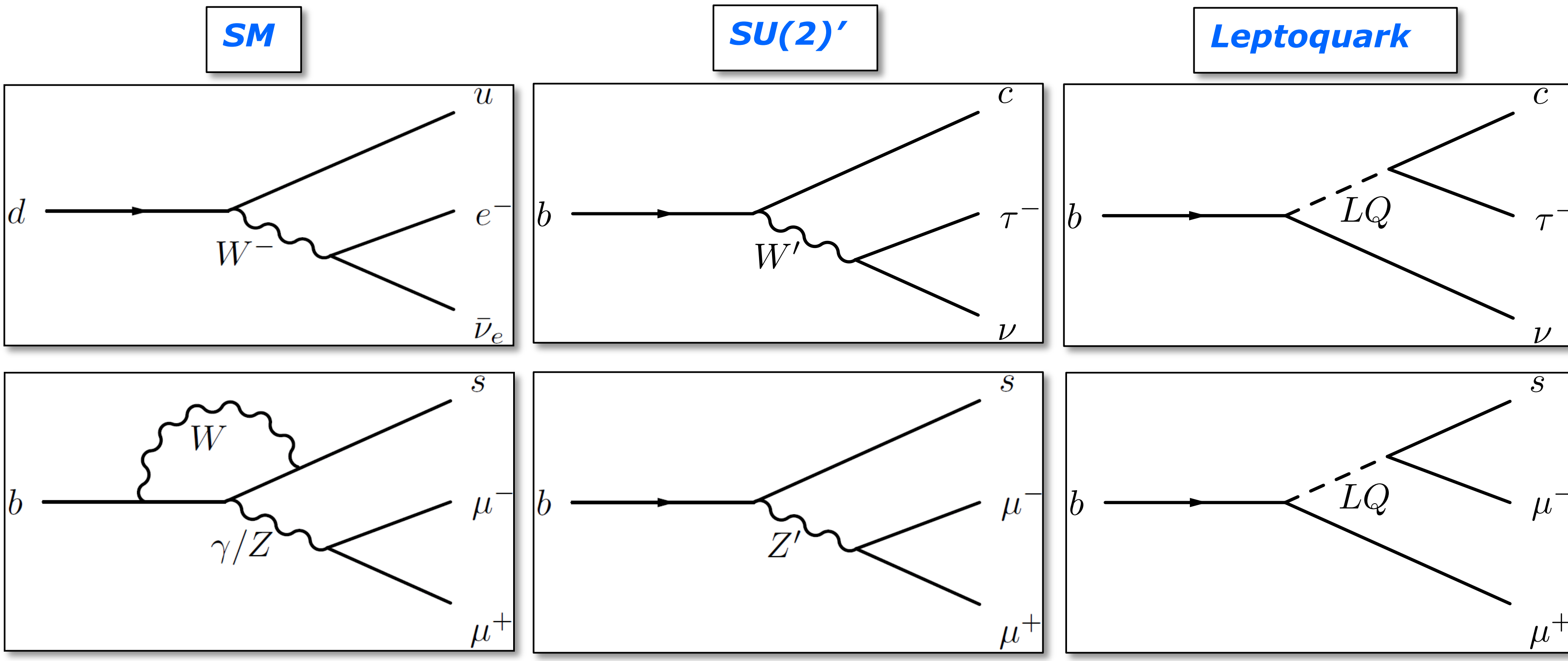


Charm-loop effects could cause a shift in C_9



Model building

- Most popular models: Z′ or Leptoquark



Historical record of indirect discoveries

Particle	Indirect			Direct		
ν	β decay	Fermi	1932	Reactor ν-CC	Cowan, Reines	1956
W	β decay	Fermi	1932	$W \to e\nu$	UA1, UA2	1983
c	$K^0 \to \mu\mu$	GIM	1970	J/ψ	Richter, Ting	1974
b	CPV $K^0 \to \pi\pi$	CKM, 3rd gen	1964/72	Υ	Ledermann	1977
Z	ν-NC	Gargamelle	1973	$Z \to e^+e^-$	UA1	1983
t	B mixing	ARGUS	1987	$t \to Wb$	D0, CDF	1995
H	e^+e^-	EW fit, LEP	2000	$H \to 4\mu/\gamma\gamma$	CMS, ATLAS	2012
?	**What's next ?**		?			?